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ESSAYS IN VEHICLE EMISSION POLICIES

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ESSAYS IN VEHICLE EMISSION POLICIES

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Dedicated to my parents for their unconditional support.

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ESSAYS IN VEHICLE EMISSION POLICIES

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The first chapter of this dissertation examines welfare impacts of a combination of subsidies to alternative fuels (AFs) and alternative fuel vehicles (AFVs), and how they compare to gasoline taxes. The particular AF examined here is ethanol that is produced from agricultural products in a small open economy. The model in this paper characterizes a country or state where gasoline is the major source of fuel for automobiles, but that also produces and consumes ethanol as an AF. Gasoline combustion is polluting and its use equals the total amount of emissions produced. Thus, a gasoline tax here is the same as an emissions tax and is the most direct environmental instrument. However, increasing gasoline taxes for pollution purposes is often politically not feasible. Thus, this paper studies how closely subsidies to alternative fuels (AFs) and alternative fuel vehicles (AFVs) emulate abatement behavior from a unit gasoline tax in a simple three sector general equilibrium model, and in the

presence of pre-existing labor taxes. The model can also be used to track the effects of each policy on outputs, exports, and fuel use. The analytical results of the model are then calibrated to data from the largest ethanol producing state in the U.S., namely Illinois. The paper finds that subsidies can achieve up to 64 percent of the welfare gains from the gasoline tax, if the uncompensated wage elasticity is low enough or the elasticities of substitution between the transportation goods is high enough.

The second chapter estimates behavior of households who jointly make discrete decisions about vehicle ownership and continuous decisions about miles driven. The paper uses seven years of data from 1995-2001 for the 35 states and union territories of India. The estimated parameters will be used to calculate elasticities of each different type of vehicle for percentage changes in petrol price per unit distance travelled and in vehicle taxes. The paper also computes income and price elasticities for petrol consumption. Two types of vehicles predominant in India are cars and two-wheelers such as motorcycles, mopeds, and scooters. The latter type of vehicle is more fuel efficient than the former. However, patterns of vehicle ownership across the country reflect a growing number of cars relative to motorcycles. This paper investigates the impact alternative policies such as taxes on petrol or on cars have on efficient methods of vehicle emission abatement in India. In particular, the chapter estimates the effect of each such policy on vehicle choice and driving behavior, and how they in turn affect emissions. The main results are summarized as follows: First, continuous choice own-price elasticities are higher for $4w$ relative to $2w$, given age, and for older vehicles relative to newer ones, within each category. Second, discrete choice own-price elasticities with respect to capital cost are higher for $2w$ relative to $4w$. Moreover, older vehicles of each type are more sensitive to higher vehicle prices relative to their newer counterparts. Third, income elasticities for discrete vehicle choices are all positive and greater than unity. Thus, higher income encourages purchase of newer vehicles of each type. Moreover, usage of vehicles rises with income, conditional on the particular vehicle choice. Finally, the paper conducts simulations that alter the price per kilometer by adding either an additional gas tax, a distance tax or an emissions tax. Results show that a distance tax reduces vehicle kilometers traveled the most, followed by an emissions tax and lastly by the gas tax. However, local emissions are reduced the most by an emissions tax, followed by a distance tax and then by a gasoline tax. Even though it would be ideal to compare the results obtained in this paper to results generated using a micro-level data set, the estimates presented here are indicative of whether a distance tax or a gasoline tax is more effective for emissions abatement in India.

The third chapter of this dissertation evaluates how information asymmetry in private automobile markets affects programs to accelerate vehicle retirement, also known as scrappage programs. We use a dynamic framework where agents have heterogenous preference for car quality. Cars can either be new, or used. While all new cars have the same quality, used cars can be of high- or low-quality. The quality of a car is perfectly correlated with emissions.

The goal of a scrappage program is to induce car owners to voluntarily scrap low-quality used cars. One key result is that in the presence of adverse selection a subsidy that maintains an active resale market unambiguously makes all types of consumers better off. However, if this option of implementing the subsidy does not exist, then the only other way to induce effective scrappage in our framework is to shut down the used car market. Welfare implications suggest that it might be better not to do anything rather than have a scrappage program such as the latter.

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Chapter 1

General Equilibrium Impacts of Subsidies to Ethanol and Ethanol-fuelled Vehicles

Vehicle ownership and its use has been increasing in developed as well as developing countries. While 60 percent of the world's vehicle fleet is held in developed countries, the ownership of automobiles has been growing the fastest in developing countries.[1] Automobiles contribute to a range of local and regional pollutants such as carbon monoxide (CO), hydrocarbons (HC), volatile organic compounds (VOCs), nitrogen oxides (NOx) and fine particulate matter. In U.S. cities, in 1999 automobiles were responsible for 51 percent of carbon monoxide (CO), 29 percent of hydrocarbon emissions, 34 percent of nitrogen oxides and 10 percent of fine particulate matter ($PM2.5$).[2] Some of these local pollutants react with sunlight in a series of complex chemical processes in the atmosphere to produce ozone or urban smog. This in turn increases risk of respiratory problems and reduces immunity to bacteria and viral infection. Automobiles also exacerbate stocks of carbon dioxide (CO_2) and other greenhouse gases (GHGs) that lead to climate change. Thus, pressures for new and more extensive forms of environmental regulation in the auto-

[1]See Harrington and McConnell, 2003.
[2]Data obtained from http://www.epa.gov/otaq/invntory/overview/pollutants.

mobile sector have grown over the years, both in developed and developing countries.

Total emissions from vehicles can be reduced either by reducing vehicle miles driven or by reducing the tailpipe emission rates per vehicle mile. The standard economic argument for efficient reduction of tail-pipe emissions in automobiles is to make the polluter pay for each unit of emissions either through a tax or a permit price, as suggested by Pigou (1920). A price per unit of emissions provides all the right incentives to reduce emissions by abating through the cheapest means such as switching to clean fuels, employing abatement technology, or by reducing use of the polluting fuel itself. Since given current technology tailpipe emissions are not observable, alternative policies such as gasoline taxes and subsidies to alternative fuels (AFs) and alternative fuel vehicles (AFVs) are often imposed to achieve efficient abatement in vehicle emissions.[3]

In this paper, I compare the general equilibrium effects of subsidies to the alternative fuel sector to more traditional market based environmental instruments such as a gasoline tax, where each of the policies are designed to reduce emissions by 1 percent. I assume that gasoline combustion in the transportation sector to be the only source of pollution. For simplicity I also assume that the amount of emissions produced per unit of gasoline used is

[3]Fullerton and West (2002) show that the efficiency results of an emissions tax can be mimicked by a complicated tax on gasoline and consumption. However, their policies depend on vehicle characteristics that can be tampered with. Moreover, such policies would be complicated to implement.

fixed. Thus, a gasoline tax is the same as an emissions tax in the model considered here. However, a gas tax is not always a politically feasible instrument since gasoline is a necessity and hence taxing it is regressive from a distributional perspective. Moreover, vehicles that contribute to pollution are in highly populated and congested urban areas. This implies that increasing the gas tax for environmental purposes makes everybody pay for the increase in pollution levels caused by a relatively small share of the population. Thus, the case for a second best scenario is the political infeasibility of implementing a gas tax. The particular type of alternative fuel I consider here is ethanol, produced from a variety of agricultural products around the world such as from corn in the U.S and from sugarcane in Brazil. The welfare effects of these alternatives are examined in the presence of pre-existing labor taxes and subsidies to ethanol and AFVs.

To compare the impact of the subsidies to that of a gasoline tax, I use a simple three sector general equilibrium model representing a small open economy with general functional forms. I then differentiate the equations to linearize them, and solve for the effects of each policy. This paper does not focus on optimal rates for each of the policy variables in the second-best framework. However, they can be calculated by differentiating the welfare function with respect to the policy variables and set each of the derivatives equal to zero to solve for the optimal gas tax, subsidy to ethanol and to ethanol-fuelled vehicle. The optimal values of these policies will fall as the price differential between gasoline and ethanol becomes lower, but they will not be reduced to zero due to the pollution generated from use of gasoline.

Ethanol is considered to have substantial environmental benefits. For instance, General Motors and the Argonne National Laboratory in 2001 conducted a life cycle assessment of a variety of alternative fuels and compared the results to that of gasoline. They use several measures to compare the relative effectiveness of all fuels such as fuel economy in miles per gallon, seconds taken to reach an acceleration speed of 60 miles per hour and the resulting green house gas (GHG) emissions from the use of each fuel. With ethanol they find that a conventional vehicle that uses 85 percent ethanol has the same fuel economy as a gasoline powered engine, but its GHG emissions are only one-third as high. Moreover, renewable ethanol combined with a fuel cell propulsion system produces more miles per gallon compared to a gasoline vehicle, and its GHG emissions are close to zero. The primary purpose for offering incentives to encourage greater use of alternative fuels such as ethanol, is to reduce dependence on imports of oil. A secondary benefit from providing subsidies to ethanol users is reduction in air pollution. Thus, a price of gasoline close to that of ethanol might induce some substitution towards consumption of cleaner fuel at the margin. However, the extent of this switch will most likely not be sufficient to correct for the negative externality generated from gasoline use. This need necessitates the use of subsidies to ethanol despite the recent phenomenon of rising gasoline prices. This paper examines the effectiveness of such incentives to ethanol as an environmental instrument when compared to existing fuel taxes.

Most papers on alternative-fuel vehicles estimate how their demand depends on various vehicle attributes.[4] These papers find that fuel cost is a significant factor determining the choice of an alternative fuel vehicle, holding other factors such as availability and other vehicle attributes constant. Proost and Van Dender (2001) is the only paper to my knowledge that compares the welfare effects of alternative fuel policies to other transport policies as possible environmental instruments and find that the latter perform better than the former. No paper to my knowledge compares the welfare effects of existing subsidies in the ethanol sector to other environmental instruments. A relevant idea in environmental economics claims that revenue-raising environmental policies could be used to lower distorting taxes elsewhere in the economy, hence producing a welfare gain beyond the environmental benefits of the policy. This idea has become known as the"double-dividend hypothesis".[5] Subsidies have been shown to be equivalent to taxes, by Fullerton and Metcalf (2002). Subsidies can help with the environment, and reduce the price of goods, which raises the real net wage, which then reduces the labor distortion just as raising the labor tax to pay for the subsidies goes the other way. This paper shows that both the gas tax and subsidies to the alternative fuel sector generate double-dividends due to the specifics of the concerned markets (explained in detail below).

Bovenberg and de Mooij (1994) have been one of the first to point out

[4]See Bunch et al. (1993), Brownstone et al. (1996), and Leiby and Rubin (1997, 2000).
[5]See for example Terkla (1984), Lee and Misiolek (1986), Oates (1991).

that the pollution taxes might not raise welfare, as they raise product prices, which reduces the real net wage and further distorts labor supply. This is the "tax interaction effect" of environmental policies. Even if revenue from pollution taxes are used to reduce labor taxes, the "revenue recycling effect" will not be sufficient to compensate for the falling real net wage from the tax interaction effect. Thus, a tax reform from a broad based labor tax to a narrow based environmental tax will typically exacerbate pre-existing distortions.[6] Thus, this stream of literature proves that one needs to take into account the details of the economy when evaluating potential environmental policies. The contribution of this paper is to combine the literature on the double dividend to that on alternative fuel policies by including pre-existing distortions when evaluating the welfare effects of existing ethanol subsidies. I also use data from the ethanol market in Illinois to compute magnitudes for the welfare impacts of environmental taxes and subsidies.

Four important trends emerge in the analysis. First, the gas tax and the subsidies induce individuals to drive less using gasoline miles, to substitute ethanol vehicles for gasoline vehicles, to consume more of the AF, and to reduce total miles driven, relative to the initial condition. Thus, in this model both types of policies achieve the substitution as well as output effects. The difference lies in the magnitudes. Under the gas tax, individuals purchase fewer gasoline vehicles, substitute fewer ethanol miles for gasoline miles, and increase

[6]Other papers in this literature include Bovenberg and der Ploeg (1994), Parry (1995), Oates (1995), Goulder (1995), Bovenberg and Goulder (1996). Fullerton and Metcalf (2001) also show that potentially subsidies can even replicate the welfare effects of taxes.

ethanol consumption by a lesser amount. Second, if the initial environmental tax is lower than its Pigouvian rate and if the polluting good is a necessity, then the emission tax rises more than proportionately for a given fall in emissions. This allows the labor tax to fall sufficiently to outweigh the negative impact of the higher overall price index on the real net wage, resulting in a double dividend in the primary factor market. Moreover, the higher gas tax reduces the income from the ownership of scarce resources that further raises labor supply. The opposite occurs under the subsidies. Even though gas taxes perform better than subsidies to the alternative fuel sector in terms of welfare in a general equilibrium framework, subsidies enjoy popular appeal. This is because farmers are a powerful lobby who are made better off as a group by the subsidies due to gain in real non-labor income. Third, despite exacerbating the labor market in my model, subsidies can raise net welfare if the size of the pre-existing distortion in the polluting sector is lower than the marginal damages from it.[7] Using an uncompensated wage elasticity of 0.15 and assuming Cobb-Douglas preferences at every node of the nested utility function, subsidies can achieve approximately 40 percent of the welfare gain under the gasoline tax. This rises to 50 percent in the absence of pre-existing distortions in the clean sector. Finally, sensitivity results show that the welfare gain from subsidies relative to that from emissions taxes can be close to 50 percent if

[7] This is not a general result. Subsidies do not necessarily exacerbate the labor market. Subsidies need taxes to be raised, but they reduce product prices and hence raise the real net wage. This latter effect can overshadow the negative impact on the labor sector due to higher taxes, thereby subsides could either not affect the labor sector or might even improve it.

either the elasticity of substitution between the two transportation services or that between aggregate consumption goods and transportation is at least as high as 2. This is also true if either the elasticity of substitution between inputs in the polluting transportation sector or that in the ethanol sector is at least 2 in magnitude. However, the welfare gains from subsidies relative to that from the gasoline tax is most sensitive to the uncompensated wage elasticity. The subsidies achieve 64 percent of the welfare results of an emission tax if the wage elasticity is reduced to 0.05.

The rest of the paper is organized as follows. Section 1 describes the model used for the policy analysis. Section 2 presents the differentiated general equilibrium model with changes in all of the policy variables and their impacts on endogenous variables of interest. Sections 2.1 and 2.2 examine the effects of the gas tax and the ethanol subsidies respectively. Section 3 provides a summary of the data sources for all the important parameters. Section 4 presents the results of the formulas derived in Sections 2.1 and 2.2. Finally, Section 5 concludes.

1.1 Model

The simple general equilibrium model in this paper assumes perfect certainty, perfect competition, perfect mobility of labor between sectors, and perfect mixing of pollutants from different sources in a small open economy. The model has three final goods and services. All of these are produced domestically, but only the goods are traded internationally. For concreteness, I think of X as an agricultural output that is always a net export, and Y as a manufacturing output that is always a net import. The third final good is transportation miles (T) is not traded in the international market.

The model has three factors of production, namely labor (L), another resource that I refer to as land (R), and the third stands for oil or any other polluting fuel (Z). Thus, the only source of pollution in my model is in the transportation sector. The rest of the notation uses the first letter of the word that identifies it such as: V = vehicles run on fossil fuel, A = alternative fuel vehicles run on ethanol or any other clean fuel, Q = quality of the environment, C = consumption bundle in utility, H = home production, and G = government provided public good in utility. Each of these goods may have any of the following superscripts: S denotes supply from domestic production, D denotes domestic demand, E denotes export, and M denotes import. For example, Y^M is the imported amount of Y. Also, each good may have a subscript that indicates its allocation, except for R since it is used only in the agricultural X sector. For example, L_X is the labor used in the production of X. Output of X^S is produced from labor, L_X, and a resource R in fixed supply, $\bar{R}$. Output Y is produced only from labor, L_Y. Thus, we define a unit of Y as the amount that can be produced using one unit of labor. Then, the main production functions for X and Y are:

$$X^S = X^S(L_X, R) \tag{1.1}$$

$$Y^S = L_Y \tag{1.2}$$

$$\tag{1.3}$$

Each of the two goods X and Y are produced with constant returns to scale. Thus, the number of firms in each sector is irrelevant. The two sectors are non-polluting, as they both use clean inputs, labor and land (resource). Even though sector X uses a factor of production that is inelastically supplied in the aggregate, each of the many firms in this sector can substitute between the two inputs and thus has a downward sloping demand for each factor of production. Hence, the aggregate demand for R slopes downward, and the intersection with a vertical total supply determines the equilibrium factor return. Thus, the factor return to R is endogenous and is a "rent" that accumulates in the hands of its owners. The numeraire good is L, or equivalently Y.

Pollution is introduced through Z, a polluting fuel used as an input in the transportation sector. It represents fossil fuel, some of which is imported and some of which is in fixed domestic supply in amount $\overline{Z}$.

$$Z^S = \overline{Z} + Z^M \tag{1.4}$$

For simplicity, emissions from combustion is assumed to be fixed per unit use of that fuel. The input to dirty transportation, Z_T, thus stands for polluting fuels as well as the pollution generated from combustion. Hence, an emissions tax in my model is the same as a gas tax and such a tax would achieve the least cost outcome of pollution control.[8]

The model introduces a third sector that produces transportation services using fuel and vehicles as inputs. Two types of fuel are used in the model:

[8]See Parry and William (1999) for policy rankings when this condition does not hold.

one is the polluting fuel, Z, and the other is an alternative fuel denoted by X_A that is assumed to be non-polluting (a use of aggregate output of X). The alternative fuel can be used only as an input in the transportation sector to fuel AFVs. Corresponding to the two types of fuel, the two types of vehicles include A, denoting AFV's that run on the clean fuel, X_A, and V, denoting vehicles that run on the polluting fuel, Z_T.[9] The two kinds of vehicles, A and V are a part of manufacturing output, Y^S, and are used as intermediate goods in the production of transportation services. Two kinds of transportation services are produced in this model, one is T_A, denoting clean transportation, and the other is T_Z, denoting dirty transportation. Hence, T_A is produced from X_A and A, while T_Z is produced from Z_T, and V. Production functions T_A and T_Z exhibit constant returns to scale. Thus, the production of T, can be represented by the following equations:

$$T = T(T_A, T_Z) \tag{1.5}$$

$$T_A = T_A(X_A, A) \tag{1.6}$$

$$T_Z = T_Z(Z_T, V) \tag{1.7}$$

The production function, T, could have any of the following alternative interpretations in our model:

(a) It could be interpreted as a production function, where firms provide a fleet of transportation services such as railroad, airlines, buses, taxis or

[9] Z_T is the only use of Z. So $Z_T = Z^S$. See equation 1.17 below.

rental cars, using fuel and vehicles as inputs. Some of those services use vehicles that run on polluting fuels such as oil and diesel, and others use vehicles that run on alternative fuels such as ethanol.

(b) The function, T, could also be interpreted as a sub-utility function, where fuel and vehicles are purchased by the consumer. The consumer does not get utility directly from fuel or vehicles, but from a combination of them that we call T, for transportation, and it is T that enters utility.

(c) Further I could interpret T as a household production function, where it is the household instead of the firm using 1.5 to produce services mentioned in (a) above. The household then "sells" these services to itself.

All of the above interpretations are identical in terms of equations and later mechanics of the model. In (a), households pay an explicit price to firms for their services, but in (b) and (c) consumers pay an implicit price for T for the services they sell to themselves. For any interpretation of T, I can use the zero profits condition to determine a price of T that the household faces, whether that is a price explicitly paid to the firm or implicitly paid to itself. Here, I interpret T as a household production function.[10]

[10] With additional complication, the manufacturing sector could also be said to use a polluting fuel, and then we could analyze pollution policy directed at the firm. But these additional features of the model would not affect any of the results below for policies directed at household use of fuel.

All individuals are identical in my general equilibrium framework, and the utility of a representative household depends on consumption levels of the two final goods, X_C and Y_C, transportation T, leisure, L_H, a government-provided good G, and environmental quality, Q. The household production function, T, implies substitution possibilities between the two forms of transportation services. If the cost of T_Z rises due to a pollution policy, then households can substitute into T_A. The efficiency loss from this switch constitutes part of the output effect. Moreover, reduced gasoline miles for a given number of vehicles implies a fall in the ratio $\frac{Z}{V}$, while increased ethanol miles per AFV implies a rise in $\frac{X_A}{A}$. This gives rise to substitution possibilities between the inputs to transportation services and reduces pollution per mile.

Since the overall scale of production is irrelevant, I use every variable above to represent the amount per household. With N identical households, the total amount of pollution from the transportation sector is NZ_T. The negative effect of pollution on environmental quality, Q, is represented by:

$$Q = Q(NZ_T); \qquad\qquad Q' < 0 \tag{1.8}$$

I can now write the utility function of the representative household as follows:

$$U = U(X_C, Y_C, T_A(X_A, A), T_Z(Z_T, V), L_H; G, Q) \tag{1.9}$$

The individual household does not get to choose the total amount of the public good, G or the overall environmental quality, Q. The representative household makes decisions subject to the following budget constraint:

$$(1-t_L)L+P_R\overline{R}+P_Z^D\overline{Z} = P_X^D X_C+(P_X^D-s_{XA})X_A+Y_C+V+(1-s_A)A+(P_Z^D+t_{ZT})Z_T \tag{1.10}$$

where P_X^D, and P_Z^D are the domestic prices of X, and Z respectively. By construction, the domestic price of Y, P_Y^D is always equal to one. P_R is the rental price of the domestic resource, $\overline{R}$. In the absence of government intervention, the prices of X_C and X_A are the same (P_X^D) since we assume that clean fuel is merely a different use of the agricultural output. Similarly, the prices of Y_C, A and V are the same in case of no policy intervention (P_Y^D) as they are all uses of the same manufacturing output. All potential environmental instruments available to the government to achieve its goal are per unit taxes or subsidies, such as: a subsidy to AFV, denoted by $s_A \geq 0$, a subsidy to the AF, given by $s_{XA} \geq 0$, and a possible tax on the polluting fuel, denoted by $t_{ZT} \geq 0$. Since the dirty fuel is available domestically in limited quantities, some of its domestic demand as an "intermediate" input in the production of transportation is met from imports. Labor is taxed at rate t_L. Thus, the net wage is given by $(1-t_L)$. Note that the fixed resources (land and the polluting fuel) are owned domestically in amounts per household of $\overline{R}$ and $\overline{Z}$ respectively.

The public good is produced according to the following function:

$$G = NL_G \tag{1.11}$$

The government budget constraint is given by:

$$\frac{G}{N} = t_L L + t_{ZT} Z_T - s_A A - s_{XA} X_A \tag{1.12}$$

where total taxable labor supply for each household is $L = L_X + L_Y + L_G$. For simplicity, the total amount of time available to each household is fixed and normalized to one. This implies that $L + L_H = 1$. In this model the most direct solution to pollution abatement would be to tax usage of polluting fuel in vehicles (t_{ZT} only). Then the question is what other combinations could work. Several countries such as the U.S. and Brazil have chosen to increase the number of vehicles that run on ethanol, by providing subsidies to A, and X_A, given by $s_A > 0$ and $s_{XA} > 0$, respectively. The welfare changes and the reduction in emission levels resulting from both policies are derived and interpreted below.

The gas tax achieves all the substitution and output effects. Consumers have the right incentives to switch from gasoline to ethanol consumption per mile, thereby reducing pollution per mile (substitution effect). It also raises the cost of producing T_Z, thereby reducing gasoline miles relative to ethanol miles, keeping total miles driven constant. Moreover, the cost of driving total miles rises and consumers react by consuming less of it. Both of these latter effects constitute the output effect in this model.

The subsidies also achieve the substitution effect and provide similar incentives as a gas tax to reduce T_Z relative to T_A. The effect on total miles driven due to the subsidies constitutes two opposing effects. One effect is that of a lower price of miles on total miles driven. The second constitutes the effect of the subsidy on the real value of income. The higher subsidy raises labor taxes that reduce the real net wage rate, and hence labor income. On the other hand, real value of non-labor income rises due to a lower composite price index. However, the lower labor income has a stronger effect on income, thereby reducing the real value of total income. This then reduces demand for miles. The income effect dominates the price effect resulting in lower total miles driven and hence achieving the output effect of the gas tax as well.[11]

Next I turn to the market clearing conditions for labor, and the fixed resource, given as follows:

$$NL = N(L_X + L_Y) + G \tag{1.13}$$

$$NR = \overline{R} \tag{1.14}$$

The labor market clearing condition assumes no international migration of labor, thereby requiring domestic demand for labor to be equal to its domestic supply. The final goods market and intermediate goods market clearing equilibrium conditions are given by:

$$X^S - X^E = X_C + X_A \tag{1.15}$$

$$Y^S + Y^M = Y_C + V + A \tag{1.16}$$

$$\overline{Z} + Z^M = Z_T \tag{1.17}$$

The balance of trade equation is defined as:

$$P_X^W X^E = P_Y^W Y^M + P_Z^W Z^M \tag{1.18}$$

[11] This might not be a general result. In cases where T is observable, the output effect could be fixed through taxation of total transportation services. See Fullerton and Wolverton (2000, 2003).

where P_X^W, P_Y^W, and P_Z^W are the fixed world prices of X, Y, and Z. Domestic price of good j is related to its world price as follows: $P_j^D = eP_j^W$, where e is the exchange rate in units of domestic currency per unit of the foreign currency. Since Y is produced using only labor, which is also the numeraire, implies that the domestic price of Y is fixed. Being a small open economy, the world prices are always fixed, implying that exchange rate is not affected by domestic policies. This in turn fixes the prices of goods X and Z.

1.2 Complete Set of Differentiated Equations

To calculate how closely subsidies to AFs and AFVs approximate a gasoline tax, I linearize the general equilibrium model described above by differentiating all the equations. Pre-existing levels of all four policy variables t_L, t_{ZT}, s_A, s_{XA} are non-zero. However, their respective changes are determined by the particular policy experiment. In each experiment at least two tax rates are changed to keep the budget balanced. For each experiment, the government calculates the revenue-neutral change in the chosen policy variables for a given emissions' target. The model then solves for the response of the endogenous variables to the particular policy. Details of the derivations are provided in the Appendix. This section presents the system of linear differentiated equations, each describing how the agents behave in response to potential changes in all of the policy variables.

First, I derive the welfare equation by totally differentiating 3.1, holding G constant. Then, I incorporate the first order conditions of utility maximization, $\frac{U_X}{P_X^D} = U_Y = \frac{U_{TA}\frac{\partial T_A}{\partial X_A}}{P_X^D - s_{XA}} = \frac{U_{TA}\frac{\partial T_A}{\partial A}}{1-s_A} = \frac{U_{TZ}\frac{\partial T_Z}{\partial Z_T}}{(P_Z^D + t_{ZT})} = U_{TZ}\frac{\partial T_Z}{\partial V} = \frac{U_H}{1-t_L} = \lambda$. Next, I differentiate the resource constraints for X, Y, and Z in 1.15, 1.16 and 1.17, and the transportation sub-utility functions in 1.6 and 1.7. Then, substituting the first order conditions and the differentiated implicit zero profit conditions for each of these sectors, dividing through by total income, I, and finally converting all changes to their respective "hat" forms and simplifying, I get:

$$\frac{dU}{\lambda I} = \frac{t_L L}{I}\hat{L} - \frac{s_{XA}X_A}{I}\hat{X}_A - \frac{s_A A}{I}\hat{A} + \frac{(t_{ZT} - \mu)Z_T}{I}\hat{Z}_T \tag{1.19}$$

where $I = (1 - t_L)L + P_R\overline{R} + P_Z^D\overline{Z}$ is total private income in the economy, and where μ is defined as $-\frac{NU_Q Q'}{\lambda}$. The term μ is the dollar value of lost utility to all individuals from a marginal increase in emissions, that is, "marginal environmental damage" (MED). A hat over a variable indicates a percentage change (e.g. $\hat{L} = \frac{dL}{L}$). The percentage changes in the policy variables do not follow the usual rule, but instead are $\hat{t_{ZT}} \equiv \frac{dt_{ZT}}{P_Z^D + t_{ZT}}$ and $\hat{s_A} \equiv \frac{ds_A}{1-s_A}$. The left hand side of 1.19 is the dollar value of the change in utility ($\frac{dU}{\lambda}$), divided by total income I.[12]

As seen from equation 1.19, any policy will have four effects on welfare: the first term is the (marginal) 'policy-swap effect' (Kim, 2002), including both the revenue recycling and tax interaction effects on labor stemming from the revenue-neutral effects of the policy change. With a distorting labor tax

[12]Later, I find expressions for the quantity changes in terms of the pre-existing tax rates and tax changes. These can be substituted into 1.19 to find dU as a function of tax rates. Then set $dU = 0$ and solve for tax rates, to find optimal tax rates.

($t_L > 0$) any further fall in labor reduces welfare. This impact is equal to the labor tax multiplied by the share of labor income in the total economy and the change in uncompensated labor supply. Much of the double dividend debate discusses whether this effect is positive such that the higher emissions tax, used to cut the labor tax, would result in more labor supply and have a positive effect on utility. The sign of this effect in this model is discussed further below. The next two terms are the tax interaction effects in the sectors for ethanol consumption and AFVs. With distorting subsidies that raise X_A or A above their first best levels (ignoring the environmental effect in the last term), a further rise in ethanol and AFVs reduces welfare. The fourth term is the (marginal) net primary environmental gain in the presence of a pre-existing gas tax. It consists of the cost of the policy from the 'output-substitution effect' (Goulder et al., 1999). This is the efficiency cost associated with substituting away from gasoline to other goods and leisure. This effect equals the reduction in gasoline consumption multiplied by the increase in the marginal cost of consuming Z_T. Thus, the net environmental benefit is the gain from abatement minus its cost.

If an initial gas tax exists, the environmental impact term can also be interpreted as the deviation from the optimum gas tax (t^*_{ZT}, the point where $t_{ZT} = \mu$). If the initial gas tax is equal to the MED, then the envelope theorem implies that a small change in fuel use ($\hat{Z}_T$) has no effect on welfare and no first order distortion arises. However, if $t_{ZT} < \mu$, then a fall $\hat{Z}_T < 0$ raises utility. On the other hand, if $t_{ZT} > \mu$, then the externality is over-corrected, and any further increase in t_Z reduces Z as well as welfare. The impact will depend on the importance of the externality (size of μ), the percentage reduction in Z_T, and the initial size of Z_T relative to the size of the economy. The first best situation with no pre-existing t_L, s_{XA} and s_A implies that changes in labor supply, ethanol consumption and the number of ethanol vehicles have no first order effect on welfare. The net welfare effects of any policy are obtained by deriving expressions for the changes in labor supply, $\hat{L}$, consumption of ethanol ($\hat{X}_A$) and the number of AFVs ($\hat{A}$), as functions of a given change in gas consumption ($\hat{Z}_T$).

To determine specific effects on labor supply, I need to know the impact of the emissions restriction on the price of T_Z, the overall price index, P_J, the real net wage, and on non-labor income. For this purpose, I follow Bovenberg and de Mooij (1994) and others in this literature by assuming that G and Q are weakly separable in utility from leisure and consumption goods, that the combination of consumption goods, represented by J (composite of C and T) is homothetic and separable from leisure, and that the combination of transportation goods is separable from non-transportation consumption goods. The separability of emissions from consumption goods and leisure in utility implies that any change in environmental quality affects consumption goods and leisure in the same way.[13] Moreover, separability of leisure from consumption

[13]Relaxing this assumption complicates the tax interaction effect. If leisure is a stronger (weaker) substitute for environmental quality relative to consumption, then this effect is strengthened (weakened). Little empirical evidence exists on the relative substitution amongst leisure, overall consumption, and environmental quality. Thus, it seems reasonable

goods in utility along with homotheticity implies that both consumption and transportation goods are equal substitutes for leisure (Deaton, 1981).[14] The household does not get to choose the optimal amount of the public good, G or the overall environmental quality, Q. With these assumptions, the utility is represented as:

$$U = U(B[J(C(X_C, Y_C), T(T_A, T_Z)), L_H]; G, Q) \tag{1.20}$$

Given G and Q, individuals first make their labor-leisure choice. At the next stage, they decide how to allocate their wage and non-wage income between consumption of transportation, T, and non-transportation goods, C. Next, households decide how to allocate income devoted to C between X_C and Y_C, and how to allocate income for T between T_A and T_Z. Finally, income allocated to T_A is spent on X_A and A, while income for T_Z is spent on Z_T and V. The consumer price index for $J(C, T)$ is defined as a weighted average of all goods purchased by the domestic consumer. Thus, it is given by:

$$P_J = \alpha_{XC} P_X^D + \alpha_{XA}(P_X^D - s_{XA}) + \beta_{YC} + \beta_V + \beta_A(1 - s_A) + (1 - \alpha_X - \beta_Y)(P_Z^D + t_{ZT}) \tag{1.21}$$

to assume weak separability implying that changes in environmental quality do not affect the relative attractiveness of consumption and leisure. For more discussion on this, see Espinosa and Smith (1995).

[14] This is a reasonable assumption as no existing empirical evidence suggests that energy intensive consumption goods are relatively stronger or weaker substitutes for leisure than non-energy consumption goods. If transportation services were a stronger (weaker) leisure substitute relative to all other consumption goods, this would strengthen (weaken) the tax interaction effects in this sector. For more on this discussion, see Parry (1997), Goulder et. al. (1997)

where α_{XC}, α_{XA}, β_{YC}, β_V and β_A are the initial consumption shares in total output of X_C, X_A, Y_C, V and A respectively. Thus, using initial values of the choice variables, $\alpha_{XC} \equiv \frac{X_C}{X^S+Y^S+\overline{Z}}$, $\alpha_{XA} \equiv \frac{X_A}{X^S+Y^S+\overline{Z}}$, $\beta_{YC} \equiv \frac{Y_C}{X^S+Y^S+\overline{Z}}$, $\beta_V \equiv \frac{V}{X^S+Y^S+\overline{Z}}$, $\beta_A \equiv \frac{A}{X^S+Y^S+\overline{Z}}$, $\alpha_X \equiv (\alpha_{XC}+\alpha_{XA})$, and $\beta_Y \equiv (\beta_{YC}+\beta_V+\beta_A)$. Totally differentiating 1.21, I get the change in the consumer price index as:

$$\hat{P_J} = \phi_{ZT}\hat{t_{ZT}} - \phi_{XA}\hat{s_{XA}} - \phi_A\hat{s_A} \tag{1.22}$$

where (again using initial price and other variables) $\phi_{ZT} \equiv \frac{(P_Z^D+t_{ZT})(1-\alpha_X-\beta_Y)}{P_J} = \frac{(P_Z^D+t_{ZT})Z_T}{I}$, $\phi_{XA} \equiv \frac{(P_X^D-s_{XA})(\alpha_{XA})}{P_J} = \frac{(P_X^D-s_{XA})(X_A)}{I}$, and $\phi_A \equiv \frac{(P_X^D-s_A)(\beta_A)}{P_J} = \frac{(P_X^D-s_A)A)}{I}$. Thus, ϕ denotes the aggregate expenditure share for each good. For example, ϕ_{ZT} is the share of aggregate expenditure on Z_T.

The weak separability imposed on the utility function allows use of six elasticities of substitution on the consumption side. Starting at the bottom of the tree, the elasticities of substitution in the two transportation sectors are defined as: $\sigma_{TA} = \frac{\hat{X_A}-\hat{A}}{\hat{P_A}-\hat{P_{XA}}}$ and $\sigma_{TZ} = \frac{\hat{Z_T}-\hat{V}}{\hat{P_V}-\hat{P_{ZT}}}$, where $\hat{P_{XA}} = -\hat{s_{XA}}$ and $\hat{P_A} = -\hat{s_A}$, $\hat{P_{ZT}} = \hat{t_{ZT}}$, $\hat{P_V} = 0$, implying:

$$\begin{aligned} \hat{X_A} &= \hat{A} + \sigma_{TA}(\hat{s_{XA}} - \hat{s_A}) & (1.23) \\ \hat{Z_T} &= \hat{V} - \sigma_{TZ}\hat{t_{ZT}} & (1.24) \end{aligned}$$

By construction, $\sigma_{TA} > 0$ and $\sigma_{TZ} > 0$. Thus for a given number of vehicles, a higher gas tax implies reduced $\frac{Z_T}{V}$. Also, for a given number of AFVs, a higher ethanol subsidy relative to the subsidy to AFVs raises the demand for ethanol. Next, because world prices of X_C and Y_C are fixed and their domestic prices are the same as their respective world prices, $\hat{X_C} = \hat{Y_C}$. The elasticity of substitution between the two types of transportation is defined as $\sigma_T = \frac{\hat{T_A} - \hat{T_Z}}{\hat{P_{TZ}} - \hat{P_{TA}}}$, which is also positive by construction. This means that if the price of clean transportation falls relative to that of polluting transportation, the number of polluting miles driven falls relative to that of clean miles (for a given number of total miles). The change in the two transportation price indices are given by $\hat{P_{TA}} = -\gamma_{XA} s_{\hat{X}A} - (1 - \gamma_{XA})\hat{s_A}$ and $\hat{P_{TZ}} = \gamma_{ZT} \hat{t_{ZT}}$, where $\gamma_{XA} \equiv \frac{(P_X^D - s_{XA})X_A}{P_{TA}T_A}$ is the share of expenditure on X_A in T_A, and $\gamma_{ZT} \equiv \frac{(P_Z^D + t_{ZT})Z_T}{P_{TZ}T_Z}$ is the share of expenditure on gas in T_Z. The expressions for $\hat{P_{TA}}$ and $\hat{P_{TZ}}$ are obtained from totally differentiating the implicit zero profit conditions and the sub-utility functions in the two transportation sectors, and substituting their respective first order conditions.

Next, the elasticity of substitution between the composite consumption good, C and the composite transportation good, T is defined as $\hat{C} = \hat{T} + \sigma_J \hat{P_T}$, where $\hat{P_T}$ is the overall transportation index. This implies that higher is $\hat{P_T}$ relative to the price index of C, lower is the consumption of total miles relative to that of composite consumption, C, for a given utility level, J. By construction, on the production side I have one elasticity of substitution between inputs. From the production function of X, I get $\hat{L_X} = \sigma_X \hat{P_R}$, where σ_X is the elasticity of substitution between L_X and R.

Define w as the real net wage, so $w = \frac{(1-t_L)}{P_J}$. Totally differentiating w, I get $\hat{w} = -\hat{t_L} - \hat{P_J}$. The next step is to derive a labor supply function, by maximizing the household's sub-utility function for the composite consumption good (J) and leisure. In other words, households maximize $B(J, L_H)$ subject to the budget constraint $P_J J = (1-t_L)L + P_R\overline{R} + P_Z^D\overline{Z}$. This yields the labor supply function: $L = L(w, I^\pi)$. Components of non-labor income, I^π include I_R and I_Z, the real values of income from land and oil reserves, respectively, where $I_R \equiv \frac{P_R R}{P_J}$ and $I_Z \equiv \frac{P_Z^D \overline{Z}}{P_J}$. These rents accumulate due to the two scarce resources, R and Z. Totally differentiating the labor supply function and substituting the changes in non-labor income as described above, I get:

$$\hat{L} = \epsilon\hat{w} + \eta(\delta_R \hat{I_R} + \delta_Z \hat{I_Z}) \tag{1.25}$$

where ϵ is the uncompensated elasticity of labor supply wage elasticity, η is the labor supply income elasticity, and $\delta_R = \frac{I_R}{I^\pi}$ and $\delta_Z = \frac{I_Z}{I^\pi}$ are the shares of income from land and oil reserves respectively. If I assume that leisure is a normal good and that the labor supply curve is not backward bending, then $\eta < 0$, and $\epsilon \geq 0$. Environmental taxes that raise the cost of transportation and hence the overall price index, P_J, positively affect labor supply through its effects on real income. While the rise in P_J lowers the real net wage, environmental revenue recycled to cut labor taxes raises it ($w = \frac{(1-t_L)}{P_J}$). If the resultant effect on real net wage is positive, then total labor supply increases as a result of pollution abatement, giving a "double dividend". In addition, P_J affects real non-labor income. In this model even if real net wage falls labor supply can still rise if non-labor income has a positive and stronger effect on it. The net result depends on the relative strengths of the two. Thus, to obtain a reduced form expression for the change in the labor supply, I need to know the change in the labor tax. For this purpose, I totally differentiate the government budget constraint in equation 1.12, set $dG = 0$, and divide it by $(1 - t_L)L$ to get the change in the labor tax as follows:

$$\begin{aligned}\hat{t_L} &= -\frac{t_L}{1-t_L}\hat{L} - \frac{t_{ZT}Z_T}{(1-t_L)L}\hat{Z_T} - \frac{(P_Z^D + t_{ZT})Z_T}{(1-t_L)L}\hat{t_{ZT}} + \frac{s_A A}{(1-t_L)L}\hat{A} \\ &+ \frac{(1-s_A)A}{(1-t_L)L}\hat{s_A} + \frac{s_{XA}X_A}{(1-t_L)L}\hat{X_A} + \frac{(P_X^D - s_{XA})X_A}{(1-t_L)L}\hat{s_{XA}} \qquad (1.26)\end{aligned}$$

Finally, I derive changes in production as functions of the policy variables. From the small economy assumption, domestic prices can change only if government policies create a wedge between domestic and world prices. Since no domestic tax applies to the production of X, the zero profit condition implies $\hat{P_X^D} = \theta_R \hat{P_R} = 0$, where $\theta_R = \frac{P_R R}{P_X^D X^S}$ is the expenditure share of land in the value of output X. Moreover, totally differentiating the production function of X and substituting the FOC, I get $\hat{X^S} = (1 - \theta_R)\hat{L_X}$, since the total availability of land is fixed ($\hat{R} = 0$). Thus, $\hat{L_X} = \frac{\sigma_X}{\theta_R}\hat{P_X^D} = 0$, thereby implying $\hat{X^S} = 0$. Hence, given fixed world prices, and no tax on the production of agricultural goods, production changes occur only in the manufacturing and energy sectors. This in turn implies no change in the demand for either factor employed in sector X. Since land is a specific factor in this sector, its demand remains unchanged, thereby fixing its price ($\hat{P_R} = 0$). Thus, I get the changes in non-labor components as $\hat{I_R} = -\hat{P_J} = \hat{I_Z}$. The scarcity rents decrease in the same proportion as the overall price index, P_J.

Labor is used in the production of Y and G and its price is determined by changes in its demand in both these sectors. The production function of Y implies $\hat{Y^S} = \hat{L_Y}$. Totally differentiating the resource constraint for labor in 1.13 and incorporating $\hat{L_X} = 0$, I get $\hat{L} = (\frac{L_Y}{L})\hat{L_Y} = (\frac{L_Y}{L})\hat{Y^S}$. Since oil production does not use labor, the change in total labor supply is allocated only to the manufacturing sector. The overall transportation price index is derived from the implicit zero profit condition in T, and substituting its FOC to get $\hat{P_T} = (1 - \alpha_{TZ})\hat{P_{TA}} + \alpha_{TZ}\hat{P_{TZ}}$, where $\alpha_{TZ} \equiv \frac{P_{TZ}T_Z}{P_T T}$ is the share of expenditure on dirty transportation in total transportation. These results hold regardless of the policy specification. Finally, I differentiate the balance of trade equations, to get:

$$P_X^D X^E \hat{X^E} = Y^M \hat{Y^M} + P_Z^D Z_T \hat{Z_T} \tag{1.27}$$

1.2.1 Benchmark Case: An Emissions Tax

Theory dictates that the most direct way to correct an externality is to place a tax at the source of the pollution. Since this model has a fixed amount of emissions per unit of gas consumed, a gas tax achieves this. The policy experiment in this section examines the general equilibrium impact of reducing a targeted level of emissions ($\hat{Z_T}$) through an increase in the gas tax, on labor tax, labor supply, exports, imports, AFV, AF, and lastly on welfare. Thus, for this particular policy experiment, I set $\hat{s_{XA}} = \hat{s_A} = 0$. The behavioral equations in this section and the next are derived by substituting the policy explicitly into the equations derived in the previous section. The welfare equation remains the same as 1.19.

To solve for the change in labor supply, I need to trace the effect of the policy on the price of the polluting fuel, and how it affects the price index of transportation, the consumer price index, and finally the net real wage. I also need to know the effect of the policy on non-labor income flows that affect labor supply. These income effects arise because the policy generates real private profits (or losses) for owners of the scarce resources through a fall (rise) in the overall price index. Then, I determine the effects of the targeted reduction in gas consumption on t_{ZT}.

The change in the overall price index, P_J in this experiment is $\hat{P}_J = \phi_{ZT}\hat{t_{ZT}}$. Hence, the change in the real net wage is $\hat{w} = -\hat{t_L} - \phi_{ZT}\hat{t_{ZT}}$. Real net wage decreases if either the labor tax or the emissions tax increases. The government uses the revenue from the gas tax to reduce the labor tax, so the resultant effect on the real net wage depends on the relative strengths of the two. Thus, the question is whether the fall in the labor tax is sufficient to outweigh the rise in the gas tax so as to prevent a fall in the the real net wage in the current framework. Real non-labor income falls by the amount that P_J rises. Substituting this in 1.25, I get $\hat{L} = \epsilon\hat{w} - \eta(\delta_R + \delta_Z)\phi_{ZT}\hat{t_{ZT}}$. The higher gas tax has a positive impact on labor supply through non-labor income effects. However, the labor supply rises if real net wage rises. The necessary change in the labor tax for the government to balance its budget when it changes t_{ZT} is modified from 1.26 to:

$$\hat{t_L} = -\frac{t_L}{1-t_L}\hat{L} - \frac{t_{ZT}Z_T}{(1-t_L)L}\hat{Z}_T - \frac{(P_Z^D + t_{ZT})Z_T}{(1-t_L)L}\hat{t_{ZT}} + \frac{s_{XA}X_A + s_A A}{(1-t_L)L}\hat{X}_A \quad (1.28)$$

This policy reduces gasoline consumption and induces switching to ethanol that raises the amount of subsidies to be given out at their initial levels, raising the increase in revenue from a higher labor tax. However, the labor tax falls if the rise in the gas tax is more than the fall in emissions and if labor supply rises. Substituting Equation B.4 into the expression for $\hat{L}$ given above, I get:

$$\begin{aligned}\hat{L} &= \frac{1}{1-t_l-\epsilon t_L}[(\epsilon(t_{ZT}\frac{Z_T}{L})\hat{Z_T} - \epsilon(s_A\frac{A}{L} + s_{XA}\frac{X_A}{L})\hat{X_A}) \\ &+ (1-t_L)(\frac{\epsilon I^\pi}{wL} - \eta(\delta_R+\delta_Z))\phi_{ZT}\hat{t_{ZT}}]\end{aligned} \tag{1.29}$$

where $I^\pi = \frac{I-(1-t_L)L}{P_J}$. The equation 1.29 consists of three effective terms: the first term measures the direct impact of the emissions reduction, the second term is the impact of the increase in AF, and the third term is the impact of the overall price change on compensated labor supply. I assume that the economy is on the "right" side of the Laffer curve, implying $(1-t_l-\epsilon t_L) > 0$. The first term says that when emissions are restricted, the environmental tax base evaluated at the initial gas tax falls, requiring the labor tax needs to rise to balance the budget, thereby reducing net wages and hence labor supply. The second term reflects the substitution effect of the gas tax. Higher ethanol consumption also requires increasing t_L and reducing L. The third term consists of two terms: the first part measures the net impact of the higher gas tax raising the overall price index, and reducing w and L. The second part of the third term measures the effect of the gas tax on non-labor income that falls, thereby increasing labor supply. The impact of the third term on L is positive. However, the net result depends on the relative strengths of the first two terms vis-á-vis the third.

Through successive steps of substitution (shown in detail in Appendix

B), I solve for the change in the gas tax for a targeted emissions reduction:

$$\hat{t_{ZT}} = \frac{C_1}{C_2}\hat{Z_T} \tag{1.30}$$

where

$$\begin{aligned} C_1 &= -[\frac{\phi_C + P_Z^D \frac{Z_T}{I} + \frac{V}{I} + P_X^D \frac{X_A}{I} + \frac{A}{I}}{L/I} - \frac{\epsilon(t_{ZT}\frac{Z_T}{I} - s_A\frac{A}{I} - s_{XA}\frac{X_A}{I})}{(1-t_L-\epsilon t_L)(L/I)}] \\ C_2 &= \sigma_{TZ}\frac{V}{L} - \frac{(1-t_L)}{1-t_l-\epsilon t_L}\phi_{ZT}(\frac{\epsilon I^\pi}{wL} - \eta(\delta_R+\delta_Z)) \\ &+ [(1-\gamma_{ZT})\sigma_{TZ} + \sigma_T\gamma_{ZT}][\frac{\phi_C + P_X^D\frac{X_A}{I} + \frac{A}{I}}{L/I} + \frac{\epsilon(s_{XA}\frac{X_A}{I} + s_A\frac{A}{I})}{(1-t_L-\epsilon t_L)(L/I)}] \end{aligned} \tag{1.31}$$

where $\phi_C \equiv \frac{P_X^D X_C + Y_C}{I}$ is the share of aggregate expenditure on C, and $\frac{C_1}{C_2} < 0$. Changes in the various price indices as a result of the higher gas tax are positive and given as follows:

$$\hat{P_J} = \phi_{ZT}\hat{t_{ZT}} = \phi_{ZT}\frac{C_1}{C_2}\hat{Z_T} \tag{1.32}$$

$$\hat{P_{TZ}} = \gamma_{ZT}\hat{t_{ZT}} = \gamma_{ZT}\frac{C_1}{C_2}\hat{Z_T} \tag{1.33}$$

$$\hat{P_{TA}} = 0 \tag{1.34}$$

$$\hat{P_T} = \alpha_{TZ}\hat{P_{TZ}} + (1-\alpha_{TZ})\hat{P_{TA}} = \alpha_{TZ}\gamma_{ZT}\frac{C_1}{C_2}\hat{Z_T} \tag{1.35}$$

Changes in ethanol consumption, the number of AFVs and clean transportation are given by substituting 1.30 in B.5:

$$\hat{X_A} = \hat{A} = \hat{T_A} = [1 + ((1-\gamma_{ZT})\sigma_{TZ} + \sigma_T\gamma_{ZT})\frac{C_1}{C_2}]\hat{Z_T} \tag{1.36}$$

Given $0 < \sigma_T = 1$ and $0 < \sigma_{TZ} = 1$, the term in parenthesis is negative if $|\frac{C_1}{C_2}| > 1$. This expression gives the extent of substitution into the clean transportation sector induced by the gas tax. Changes in the number of polluting gas vehicles (V) are given by substituting 1.30 into B.2. Changes in the number of polluting miles driven (T_Z) are given by substituting 1.30 and B.5 into A.9. Finally changes in total mileage (T) are obtained by substituting the resulting expression for $\hat{T_Z}$ and 1.36 into A.10.

$$\begin{aligned} \hat{V} &= (1 + \sigma_{TZ}\frac{C_1}{C_2})\hat{Z_T} && (1.37) \\ \hat{T_Z} &= (1 + (1-\gamma_{ZT})\sigma_{TZ}\frac{C_1}{C_2})\hat{Z_T} && (1.38) \\ \hat{T} &= (1 + [(1-\gamma_{ZT})\sigma_{TZ} + (1-\alpha_{TZ})\sigma_T\gamma_{ZT}]\frac{C_1}{C_2})\hat{Z_T} && (1.39) \end{aligned}$$

The greater is σ_{TZ}, the higher is the fall in V and T_Z. Similarly, higher is σ_T, the greater is the fall in total miles travelled. The change in real net wage is given by substituting the revenue neutral change in t_L (shown in appendix), 1.30 and B.5 into B.4 to get:

$$\hat{w} = -\frac{t_L}{1-t_L}\hat{L} + (\frac{(t_{ZT}/P_J)Z_T + \phi_{ZT}I^{\pi}}{wL})(1 + \frac{C_1}{C_2})\hat{Z_T} - \frac{(s_A\frac{A}{L} + s_{XA}\frac{X_A}{L})}{1-t_L}\hat{X_A} \qquad (1.40)$$

If $\mid \frac{C_1}{C_2} \mid > 1$, then the second term in the above equation has a positive effect on w, while the third term reduces it. The sign of the first term depends on the sign of the policy swap effect which is ambiguous. Finally, the change in welfare is obtained by substituting B.10 and 1.36 into 1.19. Magnitudes of this expression are computed in Section 3 for initial values of the parameters.

1.2.2 Impact of subsidies to alternate fuel and AFV in the presence of pre-existing gas and labor taxes

If the gas tax is not available as an environmental instrument, I examine the general equilibrium impacts of reducing a targeted level of emissions through an increase in the pre-existing levels of subsidies to ethanol and AFVs. Thus, here I set $\hat{t_{ZT}} = 0$. The welfare equation remains the same as 1.19. The subsidy combination may be thought of as an implicit tax on gasoline and polluting vehicles. In Section 4, I compare the welfare cost of this policy combination with that of the gasoline tax.

As in the previous section, to derive the welfare impacts of the policy experiment, I need to derive the impact of the policy on changes to labor supply ($\hat{L}$), ethanol consumption ($\hat{X_A}$)and the number of AFVs ($\hat{A}$). To do so I first trace the impact of the increase in the subsidies on the consumer price index, P_J. This is given as $\hat{P_J} = -\phi_{XA}\hat{s_{XA}} - \phi_A\hat{s_A}$. The fall in the overall price index due to the subsidies depends on the expenditure shares of ethanol and AFVs in after-tax income. The change in the real net wage is $\hat{w} = -\hat{t_L} + \phi_{XA}\hat{s_{XA}} + \phi_A\hat{s_A}$. Real net wage rises with the increase in the subsidies, but falls with a rise in the labor tax. If the impact of a rise in the labor tax does not outweigh the impact of the rise in the subsidies, then real net wage increases. After substituting for $\hat{A}$ from 1.23 in 1.26, I get the revenue neutral change in the labor tax as follows:

$$\begin{aligned}\hat{t_L} &= -\frac{t_L}{1-t_L}\hat{L} - \frac{t_{ZT}Z_T}{(1-t_L)L}\hat{Z_T} + \frac{s_{XA}X_A + s_A A}{(1-t_L)L}\hat{X_A} \\ &+ \frac{((P_X^D - s_{XA})X_A - \sigma_{TA}s_A A)}{(1-t_L)L}\hat{s_{XA}} + \frac{\sigma_{TA}s_A A + ((1-s_A)A)}{(1-t_L)L}\hat{s_A}\end{aligned} \quad (1.41)$$

The first three terms here are the same as those under the gas tax. The fourth and fifth terms give the extent to which t_L must rise due to the rise in the subsidies. Substituting 1.41 into the real net wage equation, I get:

$$\begin{aligned}\hat{w} &= \frac{t_L}{1-t_L}\hat{L} + \frac{t_{ZT}Z_T}{(1-t_L)L}\hat{Z_T} - \frac{s_{XA}X_A + s_A A}{(1-t_L)L}\hat{X_A} \\ &- [\frac{I^\pi}{wL}(\phi_{XA}\hat{s_{XA}} + \phi_A\hat{s_A}) + \frac{\sigma_{TA}s_A A(1 - \frac{\hat{s_{XA}}}{\hat{s_A}})\hat{s_A}}{(1-t_L)L}]\end{aligned} \quad (1.42)$$

The last term measures the impact of the lower overall price index on w. The subsidies reduce P_J which raises the real net wage. However, they also raise the labor tax, which has a stronger negative impact on the real net wage. Thus, real net wage falls due to the third term as long as $\frac{\hat{s_{XA}}}{\hat{s_A}} < 1$. The net outcome, however, depends on the labor supply. Substituting 1.42 into the expression for the change in the labor supply described above, I get:

$$\begin{aligned}\hat{L} &= \frac{1}{1-t_l-\epsilon t_L}[(\epsilon(t_{ZT}\frac{Z_T}{L})\hat{Z_T} - \epsilon(s_A\frac{A}{L} + s_{XA}\frac{X_A}{L})\hat{X_A}) \\ &- (1-t_L)(\frac{\epsilon I^\pi}{wL} - \eta(\delta_R + \delta_Z))(\phi_{XA}\hat{s_{XA}} + \phi_A\hat{s_A}) - \frac{\epsilon\sigma_{TA}s_A A(1 - \frac{\hat{s_{XA}}}{\hat{s_A}})\hat{s_A}}{(1-t_L)L}]\end{aligned} \quad (1.43)$$

The third and fourth terms are different from the expression obtained for the change in labor supply under the gas tax. The impact of the subsidies on labor supply in this model is unambiguously negative.[15]

The changes in transportation prices are given by $\hat{P_{TA}} = -(\gamma_{XA}\hat{s_{XA}} + (1-\gamma_{XA})\hat{s_A})$, $\hat{P_{TZ}} = 0$ and $\hat{P_T} = -(1-\alpha_{TZ})(\gamma_{XA}\hat{s_{XA}} + (1-\gamma_{XA})\hat{s_A})$. The subsidy combination raises the relative marginal cost of driving a gasoline mile. However, it reduces the marginal cost of driving total miles, thereby inducing consumers to drive longer distances in total. Next I need an expression for the change in the subsidies per unit reduction in emissions. However, since this section employs two subsidies, I solve for the change in ethanol subsidy as a function of the subsidy to AFVs ($\hat{s_A}$) required to achieve the emissions target. Next I solve for the optimal levels of the two subsidies by setting the change in welfare to zero. Through successive steps of substitution (shown in detail in Appendix C), the change in $\hat{s_{XA}}$ for given emissions reduction and $\hat{s_A}$ is as follows:

$$\hat{s_{XA}} = \frac{B_1}{B_3}\hat{Z_T} + \frac{B_2}{B_3}\hat{s_A} \tag{1.44}$$

[15] Fullerton and Metcalf (2001) show that subsidies can have the same efficiency outcome as emission taxes by carefully designing them such that net impact on the wage rate is zero. Despite this, labor supply would fall in this paper due to the effect of the subsidies on non-labor income components.

where

$$
\begin{aligned}
B_1 &= \frac{\phi_C + P_Z^D \frac{Z_T}{I} + \frac{V+A}{I} + P_X^D \frac{X_A}{I}}{L/I} + \frac{\epsilon(s_A \frac{A}{I} + s_{XA}\frac{X_A}{I} - t_{ZT}\frac{Z_T}{I})}{(1-t_L-\epsilon t_L)(L/I)} \\
B_2 &= \frac{\sigma_{TA}A}{L}[1 + \frac{\epsilon s_A}{1-t_L-\epsilon t_L}] + \frac{\phi_C}{L/I}(1-\alpha_{TZ})(\sigma_T - \sigma_J)(1-\gamma_{XA}) \\
&+ (\sigma_T - \sigma_{TA})(1-\gamma_{XA})[\frac{P_X^D X_A + A}{L} + \frac{\epsilon(s_{XA}X_A + s_A A)}{(1-t_L-\epsilon t_L)L}] \\
&+ \frac{\phi_A(1-t_L)}{1-t_L-\epsilon t_L}(\epsilon\frac{I^\pi}{wL} - \eta(\delta_R + \delta_Z)) \\
B_3 &= \frac{\sigma_{TA}A}{L}[1 - \frac{\epsilon s_A}{1-t_L-\epsilon t_L}] - \frac{\phi_C}{L/I}(1-\alpha_{TZ})(\sigma_T - \sigma_J)\gamma_{XA} \\
&- (\sigma_T\gamma_{XA} + \sigma_{TA}(1-\gamma_{XA}))[\frac{P_X^D X_A + A}{L} + \frac{\epsilon(s_{XA}X_A + s_A A)}{(1-t_L-\epsilon t_L)L}] \\
&- \frac{\phi_{XA}(1-t_L)}{1-t_L-\epsilon t_L}(\epsilon\frac{I^\pi}{wL} - \eta(\delta_R + \delta_Z)) \qquad (1.45)
\end{aligned}
$$

where $B_1 > 0$, $B_2 > 0$ and $B_3 < 0$. This implies that ethanol subsidy rises with higher emissions standards, but falls with larger changes in subsidies to AFVs. Substituting for the reduced form expressions of $\hat{L}$, $\hat{X_A}$ (both of which are derived in the Appendix), for $\hat{A}$ from 1.23 and for $s_{\hat{X}A}$ from 1.44 into 1.19, I get:

$$
\begin{aligned}
\frac{dU}{\lambda I} &= \frac{t_L L}{I}\hat{L}(\hat{s_A}, \hat{Z_T}) + \frac{(t_{ZT}-\mu)Z_T}{I}\hat{Z_T} - \frac{s_{XA}X_A + s_A A}{I}\hat{X_A}(\hat{s_A}, \hat{Z_T}) \\
&+ \sigma_{TA}\frac{s_A A}{I}(s_{\hat{X}A}(\hat{s_A}, \hat{Z_T}) - \hat{s_A}) \qquad (1.46)
\end{aligned}
$$

The subsidies reduce labor supply and raise ethanol consumption, both of which reduce welfare. If the initial gas tax is less than its Pigouvian level, then the emissions restriction unambiguously raises welfare. Thus, the net outcome on welfare depends on whether the negative effects on welfare outweigh the environmental gain. Setting this expression to zero I solve for the optimal change in $\hat{s_A}$ as a function of the given emissions reduction, given as follows:

$$\hat{s_A}^* = \frac{B_4}{B_5}\hat{Z_T} \tag{1.47}$$

where:

$$\begin{aligned}
B_4 &= t_{ZT}\frac{Z_T}{I} - (\frac{s_{XA}X_A + s_A A}{I})(1 + (\sigma_T\gamma_{XA} + \sigma_{TA}(1-\gamma_{XA}))\frac{B_1}{B_3}) + \sigma_{TA}s_A\frac{A}{I}\frac{B_1}{B_3} \\
&- t_L\phi_{XA}(\epsilon\frac{I^\pi}{wI} - \eta(\delta_R + \delta_Z)\frac{L}{I})\frac{B_1}{B_3} + (t_{ZT} - \mu)(1-t_L)(1-t_L-\epsilon t_L)\frac{Z_T}{I} \\
B_5 &= \frac{s_{XA}X_A + s_A A}{I}((\sigma_T - \sigma_{TA}) - (\sigma_T\gamma_{XA} + \sigma_{TA}(1-\gamma_{XA}))\frac{B_2}{B_3}) + t_L(\epsilon\frac{I^\pi}{wI} \\
&- \eta(\delta_R + \delta_Z)\frac{L}{I})(\phi_A - \phi_{XA}\frac{B_2}{B_3}) + \sigma_{TA}s_A\frac{A}{I}(\frac{B_2}{B_3} - 1)
\end{aligned} \tag{1.48}$$

where $B_4 > 0$ and $B_5 > 0$. Finally substituting 1.47 into 1.44 I solve for the optimal change in the ethanol subsidy:

$$\hat{s_{XA}}^* = (\frac{B_1B_5 + B_2B_4}{B_3B_5})\hat{Z_T} > 0 \tag{1.49}$$

1.3 Numerical Example:Assumption on Parameters

In this section I consider plausible magnitudes for the various parameters in utility equations. All data has been collected for the year 2000, for two reasons. Firstly, it marked the end of the first phase of using ethanol as an alternative to gasoline in all the states at the federal level. Secondly, that was one of the few years for which data were available on all relevant parameters. Also, I collected data for Illinois (IL) where ethanol production and usage is being strongly encouraged. Moreover, it exports ethanol and is a close fit for the model presented in this paper. I compare the two policies described above based on their respective impacts on welfare for a given reduction in pollution.

All variables are expressed as a share of Personal Income (I). The Bureau of Economic Analysis (BEA) defines personal income as that received by the residents of each state from all sources. Three sources of income exist in my model: one is labor income (wL), second is property income derived from land employed in agricultural production (farm income) (I_R), and the third comprises of earnings from oil and gas extractions (I_Z). Data for all three sources of income are obtained from the Bureau of Economic Analysis. All income estimates for each state are in current (2000) dollars. Shares for the three sources of income in total state income for both states are shown in Table 1.1.

All pre-existing taxes and subsidies include federal, state and local rates. For t_L, the income tax rate must apply to income earned from all household resources (that is, gross state personal income). I choose the average federal income tax rate to be 35 percent for all tax payers. Income tax rate for Illinois is 3 percent on average. State and local sales taxes for Illinois is 6.25 percent. All of this adds up to approximately 44 percent, accounting for the progressive federal income tax, plus state and local income taxes, plus sales and excise taxes. However, incentives depend on marginal tax rates that are higher than average tax rates. In this model, t_L represents both average as well as marginal tax rates. Thus, I settle on a labor tax rate of 44 percent.[16] The gas tax per gallon of gasoline consumption includes a federal excise tax, as well as state and local sales tax rates. This implies a marginal pre-existing gas tax rate of 43 cents/gallon of gasoline consumption for Illinois. Data for pre-existing subsidies are available only at the federal level. The subsidy rate is 54 cents/gallon of ethanol consumption.[17] The subsidy for AFV includes a federal tax credit of 2000 dollars off the price of an ethanol vehicle. This approximately amounts to a subsidy of 12 cents off every dollar on the AFV.

I follow Fullerton and Metcalf (2002) in using their number for the uncompensated labor supply elasticity, ϵ as well as for the aggregate income elasticity, η. The single value for ϵ represents an aggregate of all potential workers and all labor supply effects from changes in wages. Russek (1996) has tried to summarize all this information into one number and concludes that "the total wage elasticity for the labor supply of the economy seems to range somewhere between zero and 0.3" (p. 10). Thus, I assume 0.15 to be a reasonable value for the overall uncompensated wage elasticity. I vary this parameter to test the sensitivity of the results. Like Fullerton and Metcalf (2002), I use an average of the aggregate income elasticities for men and women found by Russek (1996) and set $\eta = -0.2$. Thus, preferences are non-homothetic.

Estimates for the elasticity of substitution between consumption and

[16] See Fullerton and Metcalf (2001) for similar calculations.
[17] http://www.ksgrains.com/sorghum/cars.html

transportation goods, σ_J, as well as that between the two types of transportation, σ_T, are not available for the specific aggregation in this paper. Hence, I choose a base value of 1.0 for both parameters and test the sensitivity of results to alternative values. Elasticities of substitution between fuel consumption and vehicle choice are also not available. Again I choose a base value of 1 for both these parameters and test for the sensitivity of results to changes in their values.

Data for the number of ethanol vehicles (A) and gasoline vehicles (V) in each state have been obtained from the Energy Information Administration (2000) and "Highway Statistics, 2000" respectively. The estimates include all private and commercial motor vehicles comprising of automobiles and light trucks. Data for gasoline consumption in each state (Z_T) and statewide gas price inclusive of all taxes (P_{ZT}) for 2000 have also been obtained from the Energy Information Administration. Aggregate expenditures as a share of state income are computed according to formulas mentioned either explicitly or implicitly in the text of the paper.

Finally, I need a measure for marginal environmental damages (μ). No sources in the literature provide an estimate of marginal damages. Freeman (1982) estimates that average damages from pollution would approximately be about 1.25 percent of GNP or higher in the U.S. in the absence of environmental policies. Like Fullerton and Metcalf (2002), I assume that total damages is 1.5 percent of total output. Expenditure share of gasoline is 2 percent of state output. Thus, marginal damages equal 75 percent ($\mu = 0.75$) of the polluting sector.[18] A summary table with all the data for Illinois is shown in Table 1.1.

1.4 Results

A summary of results using the base parameters as listed in Table 1.1 is shown in Table 1.2, for a targeted emissions reduction of 1 percent. Column (1) shows the impacts on the relevant endogenous variables under a gas tax. The rise in the gas tax is greater than the fall in the gasoline restriction, thereby raising environmental revenue ($t_{ZT}Z_T$). Hence, the labor tax is reduced sufficiently to counteract the negative effect of the higher overall price index. The tax interaction effect of the gas tax raises real net wage by 0.0014 percent. The impact of this on the labor market is discussed further below. The higher gas tax achieves the right incentives by inducing consumers to substitute away from the polluting fuel and to increase ethanol consumption by 0.0145 percent. Gasoline vehicles fall by 0.0145 percent, and AFVs coincidentally rise by the same amount. The relative implicit price of T_Z rises by 0.0721 percent, thereby reducing T_Z by 0.0576 percent. Ethanol miles increases by 0.0145 percent. The gas tax also raises the price of total miles ($\hat{P}_T$) by 0.0714 percent. This reduces total miles driven by 0.0569 percent. Hence, the gas tax achieves the right substitution as well as output effects in reducing gasoline consumption and total miles driven.

[18]This number for marginal damages is close to the 0.77 estimated by Parry and Small (2002). However, they account for externalities such as traffic congestion, air pollution and accidents.

The results of the subsidy combination are shown in column (2) of the same table. I find that the best way to achieve a 1 percent reduction in emissions using only these subsidies is to combine a 0.1856 percent higher subsidy to AFVs with a 0.0741 percent rise in the ethanol subsidy. This implies that the ethanol subsidy rises by less than that of the subsidy to AFVs. Moreover, the policies raise ethanol consumption by 0.7449 percent and AFVs by 0.8565 percent. This raises ethanol miles in a greater proportion than that achieved under the gas tax. Although theoretically it seems that since the price for total miles falls, demand for it would rise. That is not the case here. The price and income effects on T move in opposite directions. The fall in the price of T initially causes demand for T to rise. However, the subsidies cause labor income to fall (discussed in detail below), and non-labor income to rise, but the former effect outweighs the latter effect. This causes a fall in T. Whether the price effect dominates the income effect or vice-versa depends on the relative magnitudes of the income and price elasticities of total vehicle miles travelled. Goodwin, Dargay and Hanly (2003) conduct a review of studies that estimate the price elasticity of total kilometers driven, and find it to range from -0.63 to -0.10 in the long term, and from -0.17 to -0.05 in the short term. Travel behavior of Illinois residents would more likely resemble estimates at the lower end of the above ranges. Hence, the larger fall in total income relative to the fall in price results in a net fall in T. When the share of the ethanol sector rises to more than 10 percent, then the price effect starts to dominate. However, that is not the case in the data considered here. Thus, subsidies achieve all the right effects as well. This result is specific to the fuel mix considered here.[19]

The question then is how the subsidy to ethanol and AFVs compare with the gas tax in terms of net welfare? As seen from Equation 1.19, change in welfare has three effective components, shown in Table 1.3. Given the emissions target, the two policies result in the same net environmental gain (fourth term in Equation 1.19). Due to pre-existing subsidies to AFVs and ethanol, the second and third terms in Equation 1.19 show the exacerbation of pre-existing distortions in these sectors. The sum of these two terms is referred to as the clean sector distortion in Table 1.3. This distortion for both policies is negative, but negligible in size for the gasoline tax relative to that for the subsidies. This is because the subsidies induce greater consumption of ethanol. Given the base parameters in Table 1.1, the subsidies achieve 37 percent of the welfare gain relative to the ideal, but unavailable gas tax. In the absence of pre-existing distortions in the clean sector, the relative welfare gain rises to 48 percent. However, this result is sensitive to changes in certain key parameters as discussed further below.

A significant difference between the gas tax and the subsidy is the impact on the labor market. The gas tax raises the overall price index (Row 3 in Table 1.2), but the labor tax falls by more than the rise in P_J, thereby raising the real net wage. This result apparently contrasts with the one Bovenberg and

[19]Usually subsidies would raise total miles and impose additional welfare costs.

de Mooij (1994) obtained. Starting from an initial labor tax that is positive, a zero tax on the clean good, and an initial tax on the dirty good equal to the marginal environmental damage, they find that an added tax on the dirty good lowers the tax base. The additional revenue from the polluting sector does not reduce the labor tax adequately to compensate for the negative impact of the pollution tax on the real net wage. Thus, raising the gas tax from μ in their model is more distorting than raising the labor tax, as it interferes with the labor/leisure choice as well as the composition of clean versus dirty good. Hence, they conclude that given their initial conditions, the second-best optimal pollution tax must be lower than its Pigouvian level.

In my model, on the other hand, initial values of the labor tax, gas tax and subsidies to ethanol and AFVs are all positive. Furthermore, the initial gas tax is less than damages, unlike in Bovenberg and de Mooij (1994). Thus, raising the gas tax has an improvement in efficiency as well as in the environment (Double Dividend). In addition, the effect on non-labor income mentioned above increases labor supply, thereby mitigating the exacerbation in the labor market from a higher gas tax aimed at improving the environment. Thus, when gasoline consumption falls due to a higher gas tax, it reduces the demand for leisure. In addition, the initial gas tax is much lower than the marginal environmental damage (Table 1.1). Thus, the added gas tax raises adequate revenue to reduce the labor tax sufficiently. This compensates for the negative impact of the rise in P_J on the real net wage. Consequently, given that the labor supply curve is upward sloping, L rises (Row 4 in Table 1.2).

Moreover, non-labor income falls, thereby raising labor supply. However, note that even after the gas tax rises in this model, it is still far below its Pigouvian level. For these reasons the gas tax results in a "double dividend" in my model. Thus, in summary a gas tax generates a double-dividend in my model for two reasons: first, the revenue recycling effects of the gasoline tax here are stronger than the tax interaction effects because gasoline is a necessity. So a 1 percent reduction in gasoline consumption raises the gas tax by more than 1 percent, and second, non-labor income from oil and land falls as a result of the gas tax, reinforcing the increase in labor supply.

The opposite effect occurs in the labor market for the subsidies. Raising subsidies from their respective initial positive values causes the labor tax to rise by more than the fall in P_J, resulting in a fall in the real net wage, and hence a fall in labor supply. Moreover, the higher non-labor income effects also induce consumers to reduce labor supply. Thus, the subsidies further distort the labor market for the same reasons that the gas tax mitigates this distortion (Table 3).[20] Finally, since the magnitudes of these distortions are smaller than the net environmental gain for both policies, the latter outweighs the welfare cost from pre-existing distortions, and net welfare rises under both policies. However, the rise is smaller under the subsidy than under the gas tax.

[20]Fullerton and Metcalf (2001) show that "a revenue losing subsidy can be just as effective as a revenue raising policy" (Page 258). In their paper a revenue neutral increase in the subsidy to the clean good reduces the overall price index, but the labor tax can be increased to keep the real net wage and hence labor supply unchanged. The same result could be obtained in this model if the initial gas tax is assumed to be zero, if labor supply depends only on real net wage and if gasoline was an equal substitute for leisure relative to all other consumption goods.

To test the robustness of the results obtained here, I vary certain key parameters. Summary results are shown in Table 1.4. Raising the elasticity of substitution between the two types of transportation results in greater welfare gains from subsidies. This is because the higher σ_T lowers the cost of raising the subsidies, reducing the necessary rise in t_L and the corresponding fall in w. This reduces the negative impact on the labor market. Under the gasoline tax a higher σ_T reduces the size of the labor market dividend. Thus, the subsidies achieve close to 50 percent of the welfare gains from the gasoline tax when $\sigma_T = 5$. I vary σ_{TA} and σ_{TZ} from 0.3 to 2.0 since for a given number of vehicles of either type, lower mileage can be achieved from lower fuel consumption only to a limited extent. A similar argument holds for the welfare response under higher values of σ_{TA} and σ_{TZ}, both of which result in raising the welfare gains of the subsidies relative to the gasoline tax respectively. When σ_{TA} rises to 2, the subsidies achieve 48 percent of the welfare gains under the gasoline tax.

Moreover, the greater is the elasticity of substitution between aggregate consumption goods and transportation services (σ_J), the higher is the welfare gain under the subsidies while that under the gas tax remains unchanged. This is due to the fact that the subsidies reduce the relative price of T, encouraging greater substitution away from C to T. This in turn encourages greater substitution into clean miles as opposed to polluting miles, for a given emission restriction. Thus, a higher σ_J reduces the necessary rise in both subsidies, thereby reducing the distortion in the labor market. When $\sigma_J = 5$, the subsidies achieve 54 percent of the welfare gains from a gasoline tax. While each of these changes result in worsening the clean sector distortion, the percentage gain from reducing the labor market distortion outweighs the percentage loss from exacerbating the distortion in the clean sector.

Finally, testing the sensitivity of the welfare components to changes in the uncompensated wage elasticity, I find that the lower is ϵ, the higher is the welfare gain from the subsidies. If ϵ falls to 0.05, then subsidies can achieve 64 percent of the welfare gain of the emissions tax. This is because the magnitude of the welfare loss in the labor market under the subsidies reduces as ϵ falls from its base value of 0.15. The opposite argument holds as ϵ rises to 0.3.

1.5 Conclusion

I consider two policy options for reducing pollution from gasoline consumption in the transportation sector. In a simple, small open economy, general equilibrium model I assess how they compare with one another in terms of welfare with pre-existing distortions. I allow households to abate by reducing their consumption of gasoline, driving fewer gasoline miles, and switching to alternative fuel vehicles that run on ethanol. First, I find closed form analytical solutions for all general equilibrium effects of a change in policy. Then, into these solutions I insert data from Illinois as it is the largest corn and ethanol producer and exporter in the U.S.

Four important trends emerge in the analysis. First, the gas tax and the subsidies induce individuals to drive less using gasoline miles, to substitute ethanol vehicles for gasoline vehicles, to consume more of the AF, and to reduce total miles driven, relative to the initial condition. Thus, in this model both types of policies achieve the substitution as well as output effects. The difference lies in the magnitudes. Under the gas tax, individuals purchase fewer gasoline vehicles, substitute greater number of ethanol miles for gasoline miles, and increase ethanol consumption by a lower amount. Second, if the initial gas tax is lower than its Pigouvian rate and if the polluting good is a necessity, then the emission tax rises by more than the proportionate fall in the emissions restriction. This allows the labor tax to fall sufficiently and outweigh the negative impact of the higher overall price index on the real net wage. This raises labor supply, resulting in a double dividend in the primary factor market. Moreover, the fall in income from the ownership of scarce resources strengthens this effect. Third, despite exacerbating the labor market, subsidies can raise net welfare if the pre-existing distortion in the polluting sector is lower than the marginal damages from it. This welfare rise from the subsidies can be approximately 40 percent of that under the gasoline tax, and 50 percent in the absence of pre-existing distortions in the clean sector, when the subsidies are chosen optimally. Finally, sensitivity results show that the welfare gain from subsidies relative to that from the emissions tax can be at least 50 percent if either the elasticity of substitution between the two transportation services or that between aggregate consumption goods and the transportation sector is greater than one. This outcome can also be achieved if either the elasticity of substitution between inputs in the polluting transportation sector or that in the ethanol sector is at least as high as 2. However, the welfare gains from subsidies relative to that from the gasoline tax is most sensitive to the uncompensated wage elasticity. The subsidies achieve 64 percent of the welfare results of an emission tax if the wage elasticity is reduced to 0.05.

Thus, given the parameters of a representative state in the Midwest, this paper shows that ethanol and AFV subsidies encourage similar abatement effects to a gas tax. As long as the the wage elasticity is low enough and adequate substitution possibilities exist between the clean and polluting fuel, subsidies can achieve at least 50 percent of the welfare gains from the gas tax. Moreover, subsidies increase the income of the owners of scarce resources such as land and oil reserves. Thus, if they reside in a state that exports an AF and belong to strong lobbying groups, then subsidies might be more politically acceptable than gas taxes to achieve an environmental goal.

Table 1.1: Base Parameter Values

Definitions	Symbols	Illinois
Gas Price (Dollar/gallon)	$P_{ZT} + t_{ZT}$	1.55
Ethanol (E-85) price (Dollar/gallon)	P_{XA}	2.16
Gas tax (Dollar/gallon)	t_{ZT}	0.43
Ethanol Subsidy (Dollar/gallon)	s_{XA}	0.54
Subsidy on AFVs (Dollar/gallon)	s_A	0.12
Labor income tax	t_L	0.44
Uncompensated wage elasticity	ϵ	0.15
Elast. of substitution in T_Z	σ_{TZ}	1.0
Elast. of substitution in T_A	σ_{TA}	1.0
Elast. of substitution in T	σ_T	1.0
Elast. of substitution in J	σ_J	1.0
Labor supply income elasticity	η	-0.20
Marginal Environmental Damages	μ	0.75
Share of rental income in GSP	θ_R	0.007
Share of Gas consumption in GSP	ϕ_{ZT}	0.02
Share of labor income in GSP	ϕ_L	0.49
Share of T_Z in GSP	ϕ_{TZ}	0.47
Share of T_A in GSP	ϕ_{TA}	0.0001
Share of C in GSP	ϕ_L	0.53
Share of T in GSP	ϕ_T	0.47
Share of V in GSP	ϕ_V	0.37
Share of AFVs in GSP	ϕ_A	0.0003
Share of E-85 in GSP	ϕ_{XA}	0.0001
Share of gas in T_Z	γ_{ZT}	0.05
Share of E-85 in in T_A	γ_{XA}	0.57
Share of T_Z in T	α_{TZ}	0.99

The variables in the above table are defined as follows: V stands for vehicles that run on gasoline, T_Z is gasoline miles, T_A is ethanol miles, T is total miles driven, C is all consumption goods, and J is a composite of consumption and non-consumption goods. E-85 is an alternative fuel mix that constitutes 85 percent ethanol and 15 percent gasoline, but stands for pure ethanol in my model, GSP is the gross state domestic product of Illinois, and AFVs stand for alternative fuel vehicles.

Table 1.2: Impacts of two different policies, each designed to reduce gasoline consumption by 1 percent

Row No	Variables	Gas Tax	Subsidies
1	$\hat{t_{ZT}}$	1.0145	0
	$\hat{s_{XA}}$	0	0.0741
	$\hat{s_A}$	0	0.1856
2	$\hat{s_{XA}}/\hat{s_A}$	-	0.40
3	$\hat{P_J}$	0.0196	-0.0091
4	$\hat{L}$	0.0063	-0.0038
5	$\hat{t_L}$	-0.021	0.0294
6	$\hat{w}$	0.0014	-0.0204
7	$\hat{V}$	-0.00145	-1.0
8	$\hat{T_Z}$	-0.0576	-1.0
9	$\hat{P_{TZ}}$	0.0721	0
10	$\hat{P_T}$	0.0714	-0.0003
11	$\hat{T_A}$	0.0145	0.7651
12	$\hat{P_{TA}}$	0	-0.0271
13	$\hat{T}$	-0.0569	-0.9824
14	$\hat{C}$	0.0145	-1.0
15	$\hat{I_R} = \hat{I_Z}$	-0.0196	0.0091
16	$\hat{X_A}$	0.0145	0.7449
17	$\hat{A}$	0.0145	0.8565
18	$dU/\lambda I$	0.0059	0.0022

A hat over a variable indicates a percentage change (e.g. $\hat{L} = \frac{dL}{L}$). All variables in this table, except the policy variables, have been expressed in this manner. Thus, if $\hat{L} = 0.0063$ under a particular policy regime, it means that the effect of reducing gasoline consumption by 1 percent ($\hat{Z_T} = -1.0$) under the gas tax increases labor supply by 0.0063 percent. The percentage changes in the policy variables do not follow the usual rule, but instead are $\hat{t_{ZT}} \equiv \frac{dt_{ZT}}{P_Z^D + t_{ZT}}$ and $\hat{s_A} \equiv \frac{ds_A}{1-s_A}$. This means for a 1 percent reduction in gasoline consumption, the gas tax must rise by 1.015 percent of gasoline price. The variable, $\frac{dU}{\lambda I}$, is the dollar value of the change in welfare, expressed as a function of total income.

Table 1.3: Welfare Impacts under two different policies, each aims for a 1 percent cut in gasoline consumption

Row No.	Distortion	Gas Tax	Subsidies
1	Labor Distortion	0.0019	-0.0011
2	Environmental Gain	0.004	0.004
3	Clean sector Distortion	-0.00013	-0.00066
4	Net Welfare Effect	0.0059	0.0022

The above terms are defined as follows: Labor distortion (or "policy-swap effect") is $\frac{t_L L}{I}\hat{L}$, Clean Sector Distortion is $-\frac{s_{XA}X_A}{I}\hat{X}_A - \frac{s_A A}{I}\hat{A}$, and finally the Environmental Gain is $\frac{(t_{ZT}-\mu)Z_T}{I}\hat{Z}_T$. All data in the table are expressed in percentage terms. For instance, the number for labor distortion under the gas tax column (Row 1, Column 3) implies that achieving the cut in gasoline consumption through this policy contributes to a 0.0019 percent increase in welfare by reducing pre-existing distortions in the labor sector. Also, note that the net welfare effect of the gasoline tax is 0.0059 percent of total state income, while that under the subsidies is 0.0022 percent.

Table 1.4: Sensitivity Impacts on welfare in Illinois (Percentage changes)

		Lab Dist.		Clean Dist.		Welfare		W_s/W_t
Param.	Values	Tax	Sub.	Tax	Sub.	Tax	Sub.	
σ_T	2.0	.0018	-.0006	-.00003	-.0006	.0057	.0027	.48
	3.0	.0017	-.0006	-.00004	-.0007	.0056	.0027	.48
	4.0	.0016	-.0006	-.00005	-.0007	.0056	.0027	.49
	5.0	.0015	-.0005	-.00007	-.0007	.0055	.0027	.50
σ_J	2.0	.0019	-.0004	-.00001	-.0008	.0059	.0028	.48
	3.0	.0019	-.0004	-.00001	-.0008	.0059	.0028	.48
	4.0	.0019	-.0003	-.00001	-.0008	.0059	.0029	.50
	5.0	.0019	-.0001	-.00001	-.0007	.0059	.0031	.54
σ_{TA}	0.30	.0019	-.0011	-.00001	-.0047	.0059	-.0018	-
	0.50	.0019	-.0011	-.00001	-.0035	.0059	-.0006	-
	1.15	.0019	-.0011	-.00001	-.0004	.0059	.0025	.42
	1.20	.0019	-.0011	-.00001	-.0002	.0059	.0026	.45
	1.50	.0019	-.0011	-.00001	-.0001	.0059	.0027	.46
	2.00	.0019	-.0011	-.00001	-.0000	.0059	.0028	.48
σ_{TZ}	0.30	.006	-.001	-.00005	-.001	.0096	.0022	.23
	0.50	.004	-.001	-.00003	-.001	.0075	.0022	.30
	1.15	.002	-.001	-.00001	-.001	.0056	.0022	.39
	1.20	.002	-.001	-.00001	-.001	.0056	.0022	.39
	1.50	.0013	-.0012	-.00001	-.0007	.0053	.0022	.42
	2.00	.001	-.0012	.00000	-.0007	.005	.0022	.44
ϵ	0.05	.0006	-.0004	-.0001	-.0007	.0046	.0029	.64
	0.10	.0012	-.0008	-.00001	-.0007	.0052	.0026	.49
	0.20	.0025	-.0015	-.00001	-.0007	.0065	.0018	.28
	0.30	.0038	-.0021	-.00001	-.0007	.0077	.0011	.15

Sub. stands for the combination of subsidies to ethanol and ethanol-fuelled vehicles. Labor distortion (or "policy-swap effect") is $\frac{t_L L}{I}\hat{L}$, Clean Sector Distortion is $-\frac{s_{X_A} X_A}{I}\hat{X}_A - \frac{s_A A}{I}\hat{A}$, and finally the Environmental Gain is $\frac{(t_{Z_T}-\mu)Z_T}{I}\hat{Z}_T$. Thus, all variables in the above table are expressed as percentages of total state income, I. Welfare calculations are a sum of all these effects, including an environmental gain of 0.004..

Chapter 2

An Empirical Study to Evaluate Vehicle Emission Policies in India

India faces serious environmental problems in the wake of growing urbanization and an increasing population. Metropolitan cities such as Delhi, Mumbai, Chennai, Bangalore, and Kolkata are amongst the most polluted cities in the world, and their air quality continues to worsen as the country grows at an average annual rate of 8 percent. One of the pressing concerns for poor air quality in these and other urban areas in India arises from the burning of fossil fuels that emit regional pollutants such as sulfur dioxide (SO_2), and local pollutants such as carbon monoxide (CO), nitrous oxides (NO_x), and hydrocarbons (HC). These react with sunlight to cause health-damaging ozone (O_3). This paper restricts attention to local pollutants due to unavailability of data on global and regional pollutants. Until recently the lack of reliable data has hindered any study examining the impact of vehicle emission policies in place. The automobile sector in India is one of the major contributors to local air pollution. In 1996 the Central Pollution Control Board (CPCB) recorded CO concentration at some of the congested traffic intersections around the country and found it to have increased by 92 percent over it's values in 1989. In November 1996, the automobile sector was responsible for 64 percent of total air pollution in Delhi, 52 percent in Mumbai and 30 per cent in Kolkata (Agarwal (1996)). In urban areas personal vehicles contribute 27 percent of nitrogen oxides (NO_x), 74 percent of CO, and 11 percent of hydrocarbon (HC) emissions. Moreover, in 2001 the total registered number of these vehicles has grown by 62 percent from their respective values in 1996.[1]

The purpose of this paper is to estimate in India how alternative market based environmental policies such as taxes on emissions, gasoline consumption and distance traveled abate vehicle emissions. In particular, I estimate the impact of these alternative policies on distances traveled, ownership of old and new vehicles and how they in turn affect emissions. To measure these effects, I use six years of data from 1996-2001 for the 35 states and union territories of India to estimate the demand system for ownership of various automobiles and kilometers driven for various categories of privately owned vehicles. I use the estimated parameters to calculate elasticities of each different type of vehicle for percentage changes in gasoline price per unit distance traveled and in vehicle prices. I also compute income and price elasticities for gasoline consumption and examine how effective each of these policies are in improving local air quality. Finally, I conduct simulations for polices that alter the operating costs of vehicles per kilometer driven and examine each of their effects separately on the choices made and on the local air quality.

Two types of vehicles predominant in India are four-wheelers ($4w$) such

[1] www.indiastat.com.

as cars and multi-utility vehicles, and two-wheelers ($2w$) such as motorcycles, mopeds, and scooters. The latter type of vehicle is more fuel efficient than the former. However, almost two-thirds of the $2w$ on the road operate on two-stroke engines. This poor engine technology makes them account for 70 percent of HC and 50 percent of CO emissions (Ghosh, 2001). Growing numbers of $4w$ are also a serious environmental concern as their fuel efficiencies are significantly lower than that of the $2w$. Moreover, a larger proportion of the country's population owns older vehicles.

Environmental regulations for non-commercial vehicles before 1996 were very lenient, but have become radically stringent since then. All new private vehicles were required to reduce their tail pipe emissions of CO, HC, and NO_x from their respective levels in 1990. By 1996, $2w$ had to reduce their CO emissions to 36 percent, and then to 70 percent below their 1990 levels by 2000. The regulation also required $2w$ to reduce their HC emissions to 55 percent below their 1990 levels by the year 2000. In addition, $4w$ were regulated to reduce CO emissions by 58 percent and HC emissions by 73 percent by 2000.[2] Higher gasoline taxes were proposed to achieve these emissions targets, but have been difficult to implement due to political pressures from non-commercial vehicle owners. In this paper I compare how alternative incentive-based environmental policies in India can reduce emissions through their impacts on usage as well as ownership of the different types of vehicles.

[2]Society for Indian Automobile Manufactures, 2001

The least cost abatement instrument to achieve targeted reductions in emissions is an incentive based mechanism such as a pollution tax or permit system (Pigou, 1920). A price per unit of emissions provides all the right incentives to reduce emissions through the cheapest means such as lower usage of their polluting automobiles or purchasing cleaner ones in the long run. Unfortunately, however, for mobile sources such as automobiles, the technology to measure tail pipe emissions correctly is still unavailable. Thus, an emissions tax continues to be an infeasible, albeit ideal policy against which to measure the impacts of all other policies.

While inadequate technology prevents the use of instruments such as a per-unit tax on vehicle emissions, it does not necessarily preclude the use of other market based instruments that might achieve the same goal. This paper investigates how closely alternative policies such as taxes on gasoline or on distance emulate an emissions tax. Existing taxes in India include annual registration fees on vehicles, and gasoline taxes. Recently much attention has been paid with regard to how existing taxes might best be changed to meet the environmental goal.

Several papers have investigated the impact of market incentives that could be used instead of a unit tax on vehicle emissions. However, these studies obtained their parameters through calibrations rather than estimations.[3] Several other papers have estimated models of discrete choice among vehicle types

[3] For examples, see Eskeland and Devarajan (1996), Innes (1996), Kohn (1996), Plaut (1998), Sevigny (1998), Fullerton and West (2000, 2002).

incorporating the joint decision of discrete vehicle choice and distance traveled conditional on the particular vehicle bundle chosen.[4] The contribution of this paper is to estimate for India price and income elasticities for various discrete vehicle choices as well as that for continuous demand for distance traveled incorporating the interrelatedness between these two decisions. To the best of my knowledge, no study to date has used an Indian data set for years as recent as 1996-2001 to conduct this type of estimation.

The main results are summarized as follows: First, Continuous choice own-price elasticities are higher in $4w$ relative to $2w$, but higher for older vehicles relative to newer ones, within each category. Second, discrete choice own-price elasticities with respect to capital cost are higher for $2w$ relative to $4w$, and older vehicles of each type are more sensitive to higher vehicle prices relative to their newer counterparts. Third, income elasticities for discrete vehicle choices are all positive and greater than unity. Thus, higher income encourages purchase of newer vehicles of each types. Moreover, usage of vehicles rises with income, conditional on the particular vehicle choice. Finally, I conduct simulations that alter the price per kilometer faced by adding either an additional gas tax, a distance tax or an emissions tax. Results show that a distance tax reduces vehicle kilometers traveled the most, followed by an emissions tax and lastly by the gas tax. However, local emissions are reduced the most by an emissions tax, followed by a distance tax and then by a gasoline

[4]For examples, see McFadden (1979), Train (1986), Brownstone et al (1996), Goldberg (1998), Brownstone and Train (1999), and other papers reviewed in Mcfadden (2001).

tax.

The paper is organized as follows: Section 1 describes the model that I use to estimate parameters for discrete and continuous choices. Section 2 describes the data in detail, including modifications made to it for estimation purposes. Section 3 presents the results, including the elasticities for both types of choices. Section 4 conducts simulations of policies that change the price per kilometer and presents findings. Finally, Section 5 concludes.

2.1 Model

In this section, I present the model used to estimate a household's discrete decision regarding vehicle bundles and its continuous choice for distance traveled. The framework used in this paper is analogous to the one developed by Dubin and McFadden (1984). I specify a functional form for the indirect utility function conditional on vehicle choice, and then derive the continuous demand for vehicle kilometers traveled (VKT). Most models estimating discrete and continuous choices use micro-level data on households, but Fullerton, Gan and Hatori (FGH, 2005) use prefecture level data for Japan for 3 years. Since no individual household data exists for India, I follow FGH (2005) and use an aggregate data set available for India at the level of the states and union territories to estimate the parameters of my model and conduct policy simulations. Households face a discrete decision to choose from K different vehicle bundles based on type and vintage. In my paper this includes first choosing between two types of vehicles predominant in India, namely two-wheelers

($2w$) and four-wheelers ($4w$). Next, households choose the vintage of their chosen vehicle classified as old (denoted *old*) and new (denoted *new*). This gives 5 mutually exclusive and exhaustive vehicle types, including the outside option of not purchasing a vehicle at all. Thus, the bundles can be completely described by the following subscripts: (*2wn*, *2wo*, *4wn*, *4wo*, *0*), where 0 denotes the zero-vehicle bundle. Substitution between new and used vehicles makes it possible to derive how existing policies affect the vehicle composition through changes in vintage choices and new car purchase decisions. Given vehicle choice i, consumers have to allocate a fixed annual income y between VKT and another consumption good c. Thus, consumers maximize a direct utility function written as: $U(VKT_i, c)$, subject to the the following budget constraint:

$$\frac{p_g}{kpl_i} VKT_i + c_i = y - k_i \tag{2.1}$$

where p_g is the price in Rupees per liter of gasoline consumed, kpl_i is the fuel efficiency of vehicle type i in kilometers per liter. Thus, $p_i \equiv p_g/kpl_i$ is the price per kilometer faced by households that chose vehicle bundle i. The annualized cost of the particular vehicle bundle chosen is given by k_i. In this model, annualized cost of new vehicles are calculated from vehicle prices and the estimated average life of typical $2w$ and $4w$.

To derive the model for estimation purposes, a functional form for the conditional indirect utility is specified. The choice of a vehicle bundle and the conditional demand for kilometers driven is analogous to Dubin and McFadden's (1984) paper on estimating parameters for choice of appliance and conditional demand for electricity. They assume a functional form for their conditional indirect utility, and derive the demand for electricity that is linear in prices and net income, conditional on the particular appliance chosen. Goldberg (1998) and West (2004) follow their methodology in estimating the conditional demand for distance. They include a price per kilometer that is conditional on the choice of vehicle bundle. I adopt their approach, using the following functional form for the conditional indirect utility function:

$$V_i = (\alpha_{0i} + \frac{\alpha_{1i}}{\beta} + \alpha_{1i} p_i + \beta(y - k_i) + x'\gamma + \eta)e^{-\beta p_i} + \epsilon_i \tag{2.2}$$

where i indexes the vehicle type alternatives, x is a vector of of household characteristics, and η stands for unobserved consumer characteristics. In addition, α_{0i} is a bundle specific constant, while α_1, β, and the vector γ are parameters to be estimated. The error term, ϵ_i reflects unobserved vehicle attributes and is assumed to be distributed independently and identically according to the extreme value distribution. The above equation allows the price per kilometer to affect utility differently across vehicle types. For instance, a higher petrol tax increases the cost per kilometer more in $4w$ relative to the more fuel efficient $2w$. While this might discourage driving in $4w$, however, it might increase driving in the $2w$ if households have the ability to substitute between them. This might exacerbate air pollution in India as the majority of existing $2w$ operate on two-stroke engines that are significant contributors to CO and HC emissions. Indirect utility from the no-vehicle option is normalized to zero. Given this utility specification, demand for continuous VKT is derived using

Roy's identity. This equation takes the following form:

$$VKT_i = \frac{-\partial V_i/\partial p_i}{\partial V_i/\partial y} = \alpha_{0i} + \alpha_{1i}p_i + \beta(y - k_i) + x'\gamma + \eta \tag{2.3}$$

where VKT denotes distance in vehicle i as measured by the kilometers driven in that vehicle in a specific time interval. As mentioned by Goldberg (1998), the presence of the vehicle specific term $e^{-\beta p_i}$ in equation 2.2 complicates the specification. This is because it is multiplied by the error term of the utilization equation, η, making the composite error term of equation 2.2 equal to: $\eta e^{-\beta p_i} + \epsilon_i$. Unfortunately the distribution of this new error term does not preserve the advantages of the generalized extreme value distribution assumed for ϵ. Thus, I follow Goldberg's (1998) approach and apply a Taylor's series expansion around the mean price per kilometer ($\overline{p}$). This allows the resulting composite error term to become $\nu_i = \eta e^{-\beta\overline{p}} + \epsilon_i$. The first term in ν_i does not vary by vehicle type, and therefore does not affect the selection probabilities of the discrete choice model.

As shown by Dubin and Mcfadden (1984), in the context of electricity demand, the estimation of the VKT equation using Ordinary Least Squares may lead to biased parameter estimates. This is because some unobserved agent-specific attributes might be affecting the choice of a particular vehicle as well as the amount it is driven. For instance, unobserved status concerns amongst households in India might lead to the choice of new, but the fuel inefficient $4w$ as well as to higher utilization of those vehicles. Other unobserved factors might include location of households relative to their work place, safety concerns, or preferences for new styles. This implies that the $E(\eta_i) \neq 0$.

To account for the potential endogeneity for the choice-specific explanatory variables, equation in 2.3 is estimated by the instrumental variables approach, along the lines proposed in Dubin and Mcfadden (1984). Following FGH (2005), I re-write the VKT equation as follows:

$$VKT_i = \alpha_{0i} + \sum_j (\alpha_{1i} p_i \gamma_j + \beta(y - k_j)) d_j + x'\gamma + \eta \tag{2.4}$$

where j stands for the various alternatives available to the household, and d_j is a dummy equal to 1 if $i = j$. The correlation between the error term η and the $d_j's$ is corrected by instrumenting the latter with the estimated probabilities $\hat{P}_j$ obtained from the discrete choice model along with the other independent variables as instruments.

I assume that households choose alternative i if and only if the indirect utility function from that choice is higher than for any other alternative. Consequently, the probability of alternative i being chosen is:

$$P_i = Prob(V_i(p_i, y, k_i, x) > V_j(p_j, y, k_j, x) for\ all\ j\ in\ K,\ j \neq i) \tag{2.5}$$

Substituting the formula for the extreme value distribution in 2.5, I get choice probabilities that are given by the logit formulas. To specify functional forms for these probabilities, I need to account for unobserved vehicle and household characteristics. Adding an error term, u_i, to the derived logit probabilities, I estimate the discrete choice model using the following equation:

$$P_i = \hat{P}_i + u_i = \frac{exp(V_i)}{\sum_j^K exp(V_j) + 1} + u_i \tag{2.6}$$

The error term u_i reflects the difference between observed shares for each vehicle bundle and its predicted share and is assumed to be distributed independently across choices and individual observations. Equation 2.6 is estimated using Generalized Method of Moments (GMM). Using the estimation results, I solve for the predicted shares of choosing bundle i as $\hat{P}_i$. These predicted probabilities are substituted for the choice specific dummies in equation 2.4 to estimate the parameters affecting VKT chosen by each household in the data. The parameters are discussed in further detail in the Results section below.[5]

The results are used to calculate several different measures of elasticity for discrete as well as continuous choices. Using the notation of FGH (2005), I let z_i denote either k_i or p_i. Then the own- and cross-price elasticities for the discrete probabilities are as follows:

$$Own\ elasticity: \quad E_{z_i} = \frac{\partial P_i}{\partial z_i}\frac{z_i}{P_i} = \frac{\partial V_i}{\partial z_i} z_i(1 - S_i) \tag{2.7}$$

$$Cross\ elasticity: \quad E_{z_j} = \frac{\partial P_i}{\partial z_j}\frac{z_j}{P_i} = -\frac{\partial V_j}{\partial z_j} z_j(1 - S_j) \tag{2.8}$$

The formula for cross-price elasticities show that the effect of changing either the price per mile or the annual rental cost of vehicle choice j equally affects the probabilities of choosing any vehicle bundle other than j. The formulas

[5]I use a Wald statistic to test the following null hypothesis stating that the coefficients estimated in equations 2.4 and 2.6 are equal. I obtain an insignificant P-value, $Prob > chi^2 = .0961$, thereby rejecting the null. Thus, the simultaneous estimation of FGH (2005) might be appropriate here as well. However, I use the sequential estimation of Dubin and McFadden (1984), for simplicity and because it follows most existing literature, even though the two sets of coefficients are supposed to be the same as each other.

for the income elasticity of the discrete probabilities are given as follows:

$$E_{i_y} = y[\frac{\partial V_i}{\partial y} - \sum_j P_j \frac{\partial V_j}{\partial y}] \tag{2.9}$$

Own price elasticities of VKT conditional on vehicle choice i are given as follows:

$$e_{p_i} = \frac{\partial(VKT_i)}{\partial(p_i)} \frac{p_i}{VKT_i} = \alpha_{1i} \frac{p_i}{VKT_i} \tag{2.10}$$

The income or expenditure elasticity, e_y, and capital cost elasticity, e_{k_i} of continuous distance choice are given as follows:

$$\begin{aligned} e_y &= \frac{\partial(VKT_i)}{\partial(y)} \frac{y}{VKT_i} = \beta \frac{y}{VKT_i} \\ e_{k_i} &= \frac{\partial(VKT_i)}{\partial(k_i)} \frac{k_i}{VKT_i} = -\beta \frac{k_i}{VKT_i} \end{aligned} \tag{2.11}$$

All elasticities are evaluated at the sample means of VKT, y, k, and the price per kilometer for each choice, p_i.

2.2 Data

2.2.1 General Data Description

Household choices of vehicle bundles and distance traveled is best estimated using household level data on their individual demographic characteristics, income, expenditures, vehicle ownership, kilometers driven, and each chosen vehicle's characteristics including fuel efficiency in kilometers per liter, and local emissions per kilometer driven. Unfortunately, however, no such data exist at the household level in India.

I use an aggregate data set for India published by a variety of sources such as different government departments, automobile magazines, and environmental organizations, as described in further detail in the subsections below. Most of the data have been collected and made available at an affordable cost by a private company called "Indiastat".[6] All of the data used in this paper are available at the aggregate level for the 35 states and union territories in India. I treat each of the 35 states and union territories as individual units of observations, for each of the 6 years from 1996-2001. This means that each observation describes the average household in a particular state in a particular year. Pooling data across the six years and after deleting missing observations for the endogenous variables, I obtain a sample size of 183 observations.[7]

2.2.2 Data Sources

2.2.3 *Household income and expenditures on gasoline*

The consumer gasoline price in each state in India consists of two components: one is the nationalized gasoline price inclusive of central gasoline taxes, and second is a state sales tax rate that differs from one state to another. The average national gasoline price inclusive of taxes is 26 Rupees (Rs.)/litre, while the average state tax is an additional 16 percent on the central gasoline price. The Indian Petroleum and Natural Gas Statistics at the Ministry of

[6] www.indiastat.com.

[7] Three of the 35 states, namely Chattisgarh, Jharkhand, and Uttaranchal, were formed in late 2000, and thus have been included in the data only for the year 2001. Observations with missing dependant variables were deleted and account for the remaining missing data.

Petroleum and Natural Gas, Government of India is the source for the data on gasoline consumption in liters, the national gasoline price in Rs. per liter and the *ad valorem* state sales tax rate, expressed as a percentage of the centralized gasoline price. Gasoline consumption is expressed in per capita terms for estimation purposes. Gasoline expenditures are, thus, equal to the gasoline price inclusive of all taxes, times the total gasoline consumption in each state in a given year. State-wise per capita income is expressed in constant 1993-1994 rupees and is obtained from the Central Statistical Organization under the Ministry of Statistics and Program Implementation, Government of India (GOI). Table 2.1 reports summary statistics on each of these variables.

2.2.4 *Household characteristics*

Demographic characteristics used in the analysis for each state consist of the fraction of residents across age groups (0-14) and (15-59), fraction of persons enrolled in college, number of persons residing in each state per square kilometer, average family size per household, fraction of households owning homes, number of persons holding driver's licenses per household, fraction of households with at least one income earner, and the average time spent in commute per day in minutes. The source for the employment data for years 2000 and 2001 is the Indian Labor Year Book, Ministry of Labor, GOI. Data on the same variable for the remaining years are obtained from the Directorate General of Employment and Training, Ministry of Labour, GOI. Data for average family size per household, average commuting time per day, number of married couples in a household, fraction of households owning homes, and the number of persons residing in each state per square kilometer are obtained from the 2001 and 1991 Census data.[8] The fraction of licensed drivers in each state is obtained from the Motor Transport Statistics of India, Ministry of Road Transport and Highways, GOI. The education data are obtained from the Annual Reports conducted by the University Grants Commission (UGC) on all households in each state.[9] Summary statistics on each of these variables are reported in Table 2.1.

2.2.5 *Household-Owned Vehicle Characteristics*

Detailed information on vehicle bundle characteristics is not available at the household or state level. However, I have information on the fraction of residents that own each vehicle bundle in each state, including the choice of not owning a vehicle. State-wise ownership shares of new two-wheelers and four-wheelers come from the Motor Transport Statistics of India, Ministry of Road Transport and Highways, GOI. These data are the number of vehicles of each type that are reported as first time registrations in each state on an annual basis. The number of old vehicles of each type is obtained by subtracting the newly registered vehicles from the total number of registered vehicles in a particular year. These statistics represent the fraction of households that own at least one vehicle. The number of residents not owning any vehicles

[8] http://www.censusindia.net/.
[9] http://www.ugc.ac.in/

is obtained by subtracting the total number of registered vehicles from the state's population who are older than 15 years of age. I divide the result by the number of households to obtain the fraction of residents not owning any vehicles. At this stage new vehicles imply those that are less than a year old, while old vehicles constitute those that are older than a year. For my analysis, however, it is important to define the vintage of the vehicle based on their emission levels, rather than their age. To find an appropriate definition of vehicle vintages, I use an emissions data set published by the Central Pollution Control Board (2000). The National Ambient Air Quality Monitoring Program, started by the Indian government in 2000, set up a network for monitoring emissions of SO_2, NO_x, suspended particulate matter, Lead (Pb), CO and HC. Currently 328 stations around the country monitor local emissions from new and old vehicles. The program published data on how rates for each of these pollutants rise with age for different vehicle bundles. The data are provided for age groups 0-5, 5-10, and 10-15, reflecting the ratio of average emissions per kilometer (EPK) from old vehicles to that of new vehicles in each age-group. The summarized results are shown in Table 2.2. The first row of this table provides data on how average EPK for vehicles older than a year deteriorate relative to one that is less than a year old. One can see that emission rates in vehicles greater than 5 years of age deteriorate more than those that are less than 5 years old. This is due to the fact that emission norms in India became radically more binding from 1996 onwards. Thus, in the year 2000, vehicles manufactured less than 5 years of ago were subject to more stringent environmental regulation, and hence are cleaner than those manufactured prior to 1996. I use this to define new vehicles as those that are less than 5 years of age, and old vehicles as those that are more than 5 years of age. Thus, emission rates for old vehicles are expressed in terms of new ones. Table 2.3 presents the summary statistics for the choice variables. The first row of represents average ownership patterns of each vehicle bundle in India. The numbers indicate that the ownership shares of older $4w$ and $2w$ are higher than the corresponding shares of newer vehicles. Moreover, old $2w$ constitute the highest ownership share.

One of the problems with the data is that I have no information on the age distribution of old vehicles within any category. To get the average age of vehicles in each category for each observation, I estimate the following equation:

$$F_i^j = \alpha_i + \beta_i t + \gamma_1 lnpci_i + \gamma_2 cpi_i + \epsilon_i \tag{2.12}$$

where F_i^j is the fraction of residents in state i that hold vehicles of type j ($j = 2w, 4w$) that are less than a year old. Coefficients on the right hand side of the above equation are as follows: α_i is the state-specific effect that remains constant over time, and t reflects the time trend for years 1996 to 2001 and it's effect is assumed to differ across individual states. The explanatory variables are the logarithm of per capita income in state i at constant 1993-1994 rupees ($lnpci_i$), and the consumer price index of a general basket of commodities in each state (cpi_i). A vector of disturbances, ϵ_i, has been added to the above regression to reflect any unobserved heterogeneity across states.

The parameters of 2.12 are estimated using all 183 observations of the data. This regression is used to predict the number of vehicles in each state that are added to the existing stock every year (from β_i). Results of this estimation are presented in Table 2.4 for four-wheelers and in Table 2.5 for two-wheelers, as described below. The regression for $4w$ has an $R^2 = 0.7728$, while that for $2w$ has an $R^2 = 0.8602$. Both regressions show that vehicles of both type have been increasing over time with at least 90 percent significance levels. I assume that the same trend persists in years prior to 1996, in order to predict the age distribution of older vehicles added to the existing total stock in each state. Furthermore, these regressions confirm that higher per capita income increases holdings of each vehicle type, while a higher consumer price index reduces it. Using the estimates from these regressions, I predict $\hat{F_i^j}$ for past years back to 1980 for each vehicle type, i. This gives the estimated number of vehicles that are at least 16 years or older for the years 1996-2001 in my sample. However, some of the vehicles from the total stock are retired every year. To proxy for the rate at which some of the vehicles leave the market, I estimate the following equation:

$$S_{it}^j = S_{i,t-1}^j(1-\delta) + N_{it}^j; \qquad\qquad t = 1997, ..., 2001 \tag{2.13}$$

where S_{it}^j is the total stock of vehicles of type $i(=2w,4w)$ in state j at time t, N_{it}^j is the number of vehicles purchased of type i in year t and state j, and δ is the rate at which vehicles leave the market each year.[10] Adding an error

[10]Strictly speaking this is not a depreciation rate as equation 2.13 does not involve values,

term to equation 2.13, I estimate $\hat{\delta}$ using data on 183 observations from years 1996-2001 for the 35 states and union territories. This rate is estimated to be 0.0452 for $2w$ and 0.0537 for $4w$.[11] Next, I use $\hat{\delta}$, $\hat{S_{it}^{j}}$ (predicted from equation 2.13), and $\hat{F_{it}^{j}}$ (predicted from regression 2.12) to compute the total stocks of vehicles in years prior to 1996 using the following formula:

$$S_{i,t-1}^{j} = \frac{S_{it}^{j} - \hat{N_{it}^{j}}}{1-\hat{\delta}}; \qquad where\ t = 1996, ..., 1980 \tag{2.14}$$

where N_{it}^{j} is $\hat{F_{it}^{j}}$ times the number of households in each state. Total stocks of vehicles are calculated for years dating back to 1980. Finally, to get the age distribution of old vehicles, I find:

$$\hat{S_{m}^{t}} = \hat{S_{t-m}}(1-\hat{\delta})^{m}; \qquad for\ 6 \leq m \leq 15 \tag{2.15}$$

where $\hat{S_{m}^{t}}$ is the estimated number of vehicles of age m in year t, and $\hat{S_{t-m}}$ is the estimated total number of vehicles in year $t-m$. For instance, to get the number of vehicles that are 6 years of age (m) in 1996 (t), I find the number of non-depreciated vehicles in year 1990 using the $\hat{\delta}$ estimated above. From

but includes numbers. In this sense it is more like a retirement rate. However, it is not a strict retirement either as it is the same rate every year for vehicles of all ages. In this sense, it is more like a depreciation rate.

[11]

$$\begin{aligned} log(S_{it}^{2w} - S_{i,t-1}^{2w}) &= \alpha_1^{2w} + \alpha_2^{2w} log(S_{i,t-1}^{2w}) + \alpha_3^{2w} log(N_{it}^{2w}) \\ log(S_{it}^{4w} - S_{i,t-1}^{4w}) &= \alpha_1^{4w} + \alpha_3^{4w} log(S_{i,t-1}^{4w}) + \alpha_3^{4w} log(N_{it}^{4w}) \end{aligned}$$

Standard errors for $(1-\hat{\delta})$ for $2w$ and $4w$ were 0.169 and 0.249 respectively.

all this, I compute the average age of old vehicles using the following formula:

$$Age_t = \sum_{f=1}^{T} \frac{S_{t-f}(1-\hat{\delta})^f f}{S_t^{tot}} \tag{2.16}$$

where Age_t is the average age of vehicles in year t, S_{t-f} is the number of vehicles of age f in year t, and S_t^{tot} is the total stock of vehicles in year t. Thus, the average ages for old $2w$ and $4w$ are approximately 12 and 9 years, respectively (See Table 2.3).

2.2.6 *Average Market Value of Vehicles*

For this variable, I obtain retail prices for four-wheelers and two-wheelers published by the Auto Car magazine. These data are only available for the five largest metropolitan cities of India, namely Delhi, Mumbai, Kolkata, Bangalore and Chennai. Unfortunately however, this magazine started its publication from the year 1999. Thus, I need to get the price data for the remaining years in the sample. Moreover, I need to get the retail prices for the states other than those in which the metropolitan cities are situated. Before imputing the missing data, I convert these retail prices into an index. For this I use data on sales figures for each state by make and model that exists for the years 1998 to 2001 to create a weighted average of retail prices for each vehicle type. These are denoted as k_{4w}^n and k_{2w}^n, for capital costs of $4w$ and $2w$ respectively, where the weight is the market share of each model. To get prices for the rest of the states, I obtain costs of transporting vehicles from manufacturing locations of automobile companies in India to major destinations in the other states. The most popular makes/models of vehicles are manufactured in rural areas close to where the five metropolitan cities are located. The transportation costs represent region-wise truck costs of moving a vehicle per kilometer. I obtain these data by talking to several trucking companies in each region and taking an average of the reported figures. I got the cost of transporting each vehicle by assuming that approximately 4 cars fit in the most commonly used truck in India, while approximately 9 two-wheelers fit in a truck of the same size.[12] I then multiply these figures by the distance in kilometers between a major city in each non-metropolitan state and the manufacturing location closest to it. I then add the transportation cost to the retail price index of the origin city to get the vehicle price index for each of the other states. I still need to get prices for years prior to 1999. To impute these data, I regress the logarithm of capital costs for a particular vehicle type for each state ($ln(k_i^j)$) on a region-specific constant, a time trend with a state-specific slope, growth rate of the state GDP measured in constant 1993-1994 rupees ($sgdpgr_i$), a consumer price index (cpi_i), and the logarithm of per capita income ($lnpci_i$) also measured in constant 1993-94 rupees. This is represented by the following equation:

$$ln(k_i^j) = \alpha_i + \sum_{j=1}^{3} \beta_{ij} r_j t + \gamma_1 lnpci_i + \gamma_2 cpi_i + \gamma_3 sgdpgr_i + \epsilon_i \tag{2.17}$$

where the states are divided into four regions: north, south, east and west. This regression is estimated for data from years 1999-2001 for all states. Then,

[12]These figures have also been reported by the companies.

using the estimated parameters, I predict prices for years 1996-1998. Results for each vehicle type are shown in Tables 2.4 and 2.5. The state-specific dummies reflect the differences in prices largely attributed to transportation costs. The time trend coefficient shows that prices for $4w$ and $2w$ rise over time. The consumer price index in each state has a positive effect on prices at the 90 percent significance level for $4w$ and at the 95 percent level for $2w$. Next, since the analysis in this paper is based on annual budget constraints, I convert the market value for new vehicles into annual prices. For this, I divide the capital costs of new vehicles by an estimate of the service life of each vehicle type. The Central Pollution Control Board found that on average $4w$ last for 15.5 years while $2w$ last for an average of 17 years.[13] Next, I compute the annual capital costs of old vehicles that are new by our definition according to the following formula:

$$r^o_{4w} = r^n_{4w} \times 0.8^{a4w}, \qquad \textit{and} \qquad r^o_{2w} = r^n_{2w} \times 0.8^{a2w} \tag{2.18}$$

where r^n_{4w} and r^n_{2w} are the annualized capital costs of new $4w$ and $2w$, and r^o_{4w} and r^o_{2w} are the annualized capital costs of old vehicles. Moreover, $a4w$ and $a2w$ are the average ages of old vehicles within each type, computed earlier. This formula assumes an annual depreciation rate of 20 percent. Table 2.3 lists the annualized market value of each vehicle type.

[13] Central Pollution Control Board, 2000.

2.2.7 *Data on emissions of Local Pollutants*

Data on emissions per kilometer (EPK) for each individual vehicle in India are not available. However, an independent study conducted by the Center for Science and Environment in New Delhi in the year 2001 published emissions rates per kilometer of local pollutants such as carbon monoxide (CO), nitrous oxides (NO_x), and hydrocarbons (HCs) for new vehicles.[14] To compute an index for the emissions per kilometer for new vehicles, I use a weighted sum of the three local pollutants in my sample using the methodology adopted by Fullerton and West (2000). They follow Small and Kazimi (1995) in calculating the weights assigned to each pollutant according to each of their contributions to marginal environmental damages (MED). This implies assigning the highest weight to NO_x (0.495), followed by HCs (0.405) and CO (0.10).[15] I need an index for emission rates of new vehicles as defined in my model. For this, I use the emissions rates for $2w$ and $4w$ in the $(0 - 5)$ age group mentioned earlier for local pollutants, weighted by the market share of each vehicle in each state. The EPK for old vehicles of each type is obtained from the statistics published by the the National Ambient Air Quality Monitoring Program mentioned earlier that produced ratios on how each of the local pollutants deteriorated with age for $2w$ and $4w$. To get the EPK for old vehicles, I multiply these ratios to the EPK for new vehicles for each of the pollutants CO, HC and NO_x, weighted by the number of vehicles in

[14] See Agarwal et al, 2001.

[15] Small and Kazimi do not calculate the MED for CO, but mention that it is small. Thus, Fullerton and West assume a value of 0.10 for CO.

age groups $(5-10)$ and $(10-15)$ obtained from the age estimations described above. Mean values of EPK for each vehicle bundle are shown in Table 2.3. Emission rates rises with age and is the highest for old $2w$.

2.2.8 *Fuel Efficiency of Vehicles*

To my knowledge, no source in India publishes data on the fuel efficiency for used vehicles. To obtain this for older vehicles, I first estimate the relationship between fuel efficiency in kilometers per liter (KPL) and EPK for new vehicles, controlling for state-specific effects in intercept and slope, as well as accounting for higher fuel efficiency in vehicles manufactured more recently. Usually in developed countries, fuel efficiency does not deteriorate as much with age as does emissions due to environmental policies becoming increasingly stringent over the years. Since this is not the case for developing countries such as in India where environmental awareness has gained attention only since the late 90s, I assume that the relationship between fuel efficiency and emission rates remains the same for both old and new vehicles, holding all else constant. Thus, the fuel efficiency for new vehicles is given as follows:

$$lnfe_i^j = \alpha_i + \beta_{1i} EPK_i^j + \beta_{2i} t + \epsilon_i \tag{2.19}$$

where $lnfe_i^j$ is the logarithm of the fuel efficiency for new vehicle of type j in state i using observations for all states from 1996-2001. Tables 2.8 and 2.9 give the results of this regression. The regression for $2w$ has an $R^2 = 0.8731$, while that for $4w$ has one equal to 0.8274. For both regressions, EPK has a highly significant negative impact on fuel efficiency. This can also been seen from the descriptive statistics provided in Table 2.3. For instance, without controlling for other variables, Table 2.3 shows that EPK is lower when the fuel efficiency is higher within each vehicle type. Moreover, fuel efficiency in India has improved over time as indicated by the significant positive slope on time trend in each of the two estimations. Next, I use the estimated parameters to predict the relationship between fuel efficiency and EPK for old vehicles using the emissions data obtained for the latter described in the earlier section. Table 2.3 lists the mean values of this variable for each vehicle bundle.

2.2.9 *Gasoline price per kilometer and Gasoline Consumption*

The Ministry of Petroleum and Natural Gas, Govt. of India publishes a report on the Indian Petroleum and Natural Gas Statistics every year. This provides data on gasoline consumption and on the *ad valorem* sales tax rates on gasoline that varies across states. Average consumption of gasoline across all states in India is 522.05 litres, while the average gasoline price inclusive of taxes is 30.12 rupees, both of which are shown at the bottom of Table 2.2. Multiplying gasoline consumption with the state-wise gasoline price, I get gasoline expenditures. I multiply the gasoline price (in rupees per litre) with the fuel efficiency of each vehicle bundle, to get the price of distance, p_i (in rupees per kilometer). I assume that gasoline expenditures are the only marginal costs of driving. Average of these figures are provided in Table 4 for each vehicle category

2.2.10 *Vehicle kilometers traveled (VKT).*

Since VKT is not observed directly for Indian households, following FGH (2005) I use data on the average gasoline expenditures, E_n, (in rupees per household) for each state and divide it by p_i (in rupees per kilometer) to get VKT (in rupees per household). Thus, the left-hand side of the equation 2.4 becomes (E_n/p_i).

2.2.11 *Descriptive Statistics*

Summary statistics are presented in Table 2.3. Average figures reflect the fact that the proportion of older vehicles is higher for both $2w$ and $4w$. Moreover, fuel efficiency is higher in $2w$ relative to that in $4w$. Despite this, the emissions per kilometer for old $2w$ is higher relative to that of old $4w$. This is due to the use of two-stroke engine technology in $2wo$ that reduces their environmental advantage from higher fuel efficiency. The emission rates for $4wn$ are the lowest. Average VKT patterns show that the $4w$ are driven almost twice as much as the $2w$. This could be because the $2w$ are mostly used for short distances, while the former are used for short as well as long trips. Combining the emission rates with the distances traveled by each vehicle bundle, I find that the worst contributors to local pollution are $2wo$, then $2wn$, next comes $4wo$ and finally are the $2wn$. The table also presents some preliminary trends in the data without controlling for other variables. Patterns of vehicle ownership for old $4w$ are very similar across regions. However, $2wo$ are the most popular in the North, followed by the Western regions.

Households living in the most populated regions tend to own more $2w$ relative to $4w$, but also seem to purchase older vehicles with each type relatively more than newer ones. However, it is encouraging to note that households that tend to concentrate relatively more on newer vehicles are the ones with greater than average income levels, and with at least one employed member. Households that tend to purchase a greater share of older vehicles of each types are those that own homes and at least have a high-school education. This could be attributed to limited borrowing in financial markets.

2.3 Results

Estimation of the model described in Section I is conducted in two stages. The first stage uses a logit specification to estimate the discrete choice shares as functions of household characteristics and vehicle bundle characteristics. Then, the second stage estimates the demand for vehicle kilometers traveled using the methodology described in Section I.

2.3.1 Stage 1: The Discrete Choice of Vehicle Bundle

The logit probabilities in equation 2.6 are estimated by Generalized Method of Moments (GMM). Using data on each state's proportion of each of the vehicle choices, I get the following five bundles: $(P_{4wn}, P_{4wo}, P_{2wn}, P_{2wo}, P_0)$. Due to problems of collinearity, I use the first four shares to estimate the coefficients affecting the discrete choices independent of the continuous distance choice. The results are reported in Table 2.10. The likelihood of owning vehicles increases for households living in densely populated regions, with greater income earners, having larger family sizes and with more members greater than the age of 15 years. On the other hand, the opposite is true for families with more children, with greater number of educated members and those owning homes. In India, families invest in children, education and homes and each of these are considered substitutes to vehicle ownership. Shares of each vehicle type in the North are not significantly different from that in the South, which is used as the base regional dummy. However, vehicle shares in each category in the East are significantly lower than those in the South, while those in the West are significantly higher. One set of parameter estimates of the discrete choice model are of special interest: the coefficient on "Price per kilometer". It gives insight into consumer preferences for fuel efficiency. These can be used to assess the effects that price changes resulting from alternative policies may have on the composition of the vehicle fleet and on VKT. In my paper, the coefficients on price per kilometer for all four vehicle choices are negative and significant. Thus, higher gas prices discourage ownership of vehicles. However, higher net income increases vehicle shares. This could pose a significant problem for India from an environmental perspective if the shares encourage ownership of the more polluting vehicles. The elasticities calculated below (Tables 2.11 and 2.12) can be used to interpret more clearly how particular vehicle shares change with income, vehicle capital costs and prices per kilometer. The own and cross-price elasticities of demand for discrete vehicle choice with respect to gas prices are given in Table 2.11. Own and cross elasticities for discrete choices with respect to capital cost are given in Table 2.12, along with the respective income elasticities for each vehicle type. As seen from Table 2.11, a higher price per kilometer reduces the market shares of older vehicles more than their newer counterparts, for each vehicle type. This shows that households in India switch to more fuel-efficient vehicles within each type when faced with higher marginal costs per kilometer. Thus, if gas prices rise by one percent, then shares of older $4w$ fall by 0.36 percent while that for newer $4w$ falls by 0.01 percent. Moreover, given age, shares of $2w$ are more sensitive to higher prices per kilometer than that of $4w$. This is because $2w$ in India are owned by lower income groups who view vehicles as a luxury good and hence are more sensitive to higher prices. This is also encouraging for the purposes of emissions abatement as the $2w$ in India are the most polluting vehicles on the road. Table 2.12 shows that the own-price elasticities with respect to capital cost are also higher for older vehicles in each category. Moreover, for a given age, the $2w$ are more sensitive to increases in capital costs relative to $4w$. The last row of Table 2.12 shows that the income elasticities for discrete vehicle choices are all positive and greater than unity, reflecting the fact that in India all categories of vehicles are luxury goods. Thus, income raises the shares for newer vehicles relatively more than that for older ones within each type. It also raises shares of $4w$ relatively more than that for $2w$ for a given age. Also, the shares of not owning any vehicle falls as income rises.

2.3.2 Stage 2: Estimation of the Demand for Vehicle Kilometers Traveled

In the second stage of the regression analysis, I substitute the estimated vehicle shares from Stage 1 to consistently estimate equation 2.4 using Ordinary Least Squares. Results of this regression are shown in Table 2.13. As expected, the results show that higher operating costs per kilometer decrease VKT while income increases it. Households that drive their vehicles less, given their particular vehicle choices are the ones that have larger families, live in densely populated areas, and own homes. On the other hand, households that drive greater distances, given their vehicle choices, have at least one employed member, have a greater share of members over the age of 15, are educated and have children. Table 2.14 gives the elasticities for continuous choice with respect to income, price per kilometer, and capital costs of each vehicle bundle. Income raises the distance traveled amongst households in India, and the elasticity on average is 0.22. This seems higher than the ones obtained recently by others in the literature. For instance, West (2004) finds an expenditure elasticity calculated at sample means as 0.02. Mannering and Winston (1985) find a VMT elasticity of 0.04 on average. Hensher et al. (1992) report VMT elasticities ranging from 0.05 to 0.14. Archibald and Gillingham (1981) is the only other study to my knowledge that estimates a VMT expenditure elasticity ranging from 0.23 to 0.47, numbers that are closer to my estimate.

Table 2.14 also shows that higher costs per kilometer reduce distance traveled in all vehicle bundles, but mostly in $4wo$. I find that given vehicle type, VKT in older vehicles is more responsive to higher gasoline price per kilometer. On the other hand, given vehicle vintage, distance driven in $4w$ is more sensitive to a unit increase in the gasoline price per kilometer than that in $2w$. This is intuitive since a higher price per kilometer increases marginal costs of the fuel inefficient $4w$ the most. The own-price per kilometer elasticities for VKT in my paper range from -0.39 to -5.15. These estimates are also much higher than those obtained in the literature. For example, Wall et al. (1994) has a VMT price elasticity that ranges from -0.120 to -0.583. Berkowitz et al. (1990) estimate a VMT price elasticity of -.21. Similarly Mannering and Winston (1985) find a VMT price elasticity of -.228, and Hensher et al.'s (1992) results range from -.28 to -.39. Sevigny's (1998) estimates also seem slightly higher than the others and ranges from -.85 to -.94. West (2004) also obtains estimates ranging from -1.51 for the lowest income decile to -.75 for the highest. If my estimations were to be conducted at the household level in India, I would expect the VKT price elasticities to be closer to West's estimates for the lower deciles. The higher estimates for the VKT price elasticities obtained in this paper can be attributed to the use of an aggregate data set. However, because of the way the vehicle bundles are defined in this paper, these elasticities are not strictly comparable to estimates from previous studies. As a last note, the capital cost elasticities are negative for VKT traveled in all the bundles, but VKT in $2wo$ is the most sensitive, while that in $4wn$ is the least sensitive. Also, VKT in the older vehicles of each type are more sensitive to changes in capital costs than the newer ones.

2.4 Simulation

Using the parameters estimated in the previous section, I now compare the effects of alternative policies on VKT, emissions, and the ownership shares of the various vehicle bundles. I compare the results obtained in this section to the current situation that incorporates all existing taxes such as a gas tax, or other forms of vehicle taxes such as age taxes or registration fees. Since VKT in equation 2.4 and utility in equation 2.2 depend on the price per kilometer and the annualized capital cost, I translate each policy into its "model equivalent form". Moreover, in this paper I focus on the effects of one policy at a time. I consider the effects of policies that change the price per kilometer driven. This could include a tax per liter of gasoline consumption (t_g), a tax per unit distance traveled (t_d), or a tax per unit of local emissions (t_e). To incorporate all such policies, I follow FGH (2005) and write the price per kilometer in the following form:

$$p_i^* = [\frac{p_g + t_g}{KPL_i} + t_e EPK_i + t_d] \tag{2.20}$$

The existing gasoline tax is included in p_g. Thus, any $t_g > 0$ in 2.20 represents an added tax. I conduct simulations for three different taxes that I describe in further detail below. The first experiment considers the impact of an emissions tax in rupees per gram of emissions, t_e. When this rate is multiplied by the EPK in grams per kilometer, it yields the tax in rupees per kilometer. This policy is currently not available, as the equipment to measure emissions accurately is still not cost effective. However, it is known to be the least-cost instrument for reducing emissions, and it offers an important yardstick from which to assess the merits of alternative feasible policies. I assume that households are well informed regarding the effects of their vehicle choices on emissions rates. Thus an emissions tax might induce households to undertake a variety of abatement activities such as to purchase newer, more fuel efficient vehicles or to drive less in their existing vehicles.

I also examine the effects of increases in the gasoline tax per liter, t_g. This is a feasible alternative, and I evaluate how it measures up against an ideal emissions tax per kilometer in India. Finally, I look at a distance tax per kilometer driven, t_d, to see how it compares to the other two environmental taxes with regard to emissions reduction. Although distance is more observable than emissions, drivers in India could still tamper with the odometer. Theoretically, however, this tax should perform better than a gas tax as it avoids the "rebound effect" referred to by Harrington and McConnell (2003). In other words, a gasoline tax shifts consumers towards more fuel efficient $2w$ in India, and drive them more resulting in higher emissions. This higher fuel efficiency offsets the higher price per kilometer faced by consumers. On the other hand, the only way households can reduce the effects of higher operating costs under a distance tax in the short run is by reducing distance traveled.

Currently the average gasoline tax in India is 30.12 rupees per liter. I add a gasoline tax that varies from 5 percent to 100 percent of this existing gasoline price. The results are shown in Table 2.15. I then average across vehicle choices to calculate how much each gas tax rate adds to the existing price per kilometer. Using this change in p_i, I then calculate equivalent changes in the other two taxes, t_e, and t_d. All policies reduce VKT, but a distance tax reduces it the most. Then comes the emissions tax and finally the gas tax. In the short run both emissions and distance taxes induce households to reduce distance. However, each of these policies affect usage differently across vehicle bundles. An emissions tax discourages driving in the vehicles with higher emission rates, namely the $2w$, but a distance tax raises marginal cost equally across all vehicle choices, thereby reducing distance traveled by a greater amount than an equivalent emissions tax. However, the fact that a distance tax performs better than an equivalent gas tax confirms the aforementioned theory about the "rebound effect" of a gasoline tax. An increase of 0.27 rupees per kilometer over the existing gasoline tax achieves a 10 percent reduction in VKT under the gasoline tax. An equivalent distance tax reduces distance by close to 24 percent, while an emissions tax reduces it by about 20 percent.

Comparing the effects of each policy on the ownership shares of the different vehicle bundles estimates show that the least cost emissions tax reduces the shares of $2wo$ the most, followed by $2wn$, since these vehicles have the highest emissions rates. Moreover, the emissions tax induces purchase of newer $4w$ and that of the zero vehicle bundle. Shares of $4wo$ rise only slightly from their current levels. Thus, households in India shift from $2w$ to $4w$ in response to an emissions tax.

Comparing the effects of a distance tax on the relative shares of the five vehicle bundles, the distance tax reduces shares of old $4w$ and $2w$, and raises that of new $2w$ and the zero vehicle bundle. One possible explanation for this could be that much of the benefits from owning $4w$ in India come from driving them around as a display of status. Thus, a higher marginal cost per kilometer reduces the benefits of owning a $4w$ relatively more than a $2w$, thereby encouraging households to switch from the former to the latter.

Finally, comparing the impacts of the gas tax on the vehicle bundles, estimates show that the gas tax reduces shares of both old and new $4w$. This is expected, as under the gasoline tax households switch to vehicles with higher fuel efficiencies so as to offset the higher price per kilometer imposed by the tax.

2.5 Conclusion

The contribution of this paper is to estimate for India the price and income elasticities for various discrete vehicle choices as well as that for continuous demand for distance traveled. To the best of my knowledge, no study till date has used an Indian data set for years as recent as 1996-2001 to conduct the above estimation. The main results are summarized as follows: First, continuous choice own-price elasticities are higher for $4w$ relative to $2w$, given age, and for older vehicles relative to newer ones, within each category. Second, discrete choice own-price elasticities with respect to capital cost are higher for $2w$ relative to $4w$. Moreover, older vehicles of each type are more sensitive to higher vehicle prices relative to their newer counterparts. Third, income elasticities for discrete vehicle choices are all positive and greater than unity.

Thus, higher income encourages purchase of newer vehicles of each type. Moreover, usage of vehicles rises with income, conditional on the particular vehicle choice. Finally, I conduct simulations that alter the price per kilometer by adding either an additional gas tax, a distance tax or an emissions tax. Results show that a distance tax reduces vehicle kilometers traveled the most, followed by an emissions tax and lastly by the gas tax. However, local emissions are reduced the most by an emissions tax, followed by a distance tax and then by a gasoline tax. Even though it would be ideal to compare the results obtained in this paper to results generated using a micro-level data set, the estimates presented here are indicative of whether a distance tax or a gasoline tax is more effective for emissions abatement in India.

Table 2.1: Summary Statistics of the Demographic Variables

Variable Name	Variable Definition	Means
Famsize	Average number of people in a household	5.535 (0.719)
Education	Fraction of residents enrolling in college	0.142 (0.699)
Pop. Dens.	Number of persons per square kilometer	992 (2050)
Pop-14	Fraction of residents in age-group (0-14)	0.308 (.0534)
Pop-59	Fraction of residents in age-group (5-59)	0.553 (0.077)
Employment	Fraction of households with at least one income earner	0.6193 (1.145)
Marr. Coup.	Number of married couples per household	1.0834 (0.312)
Houses owned	Fraction of households that own homes	0.7736 (0.1271)
PCI	Income in constant 1993-94 Rupees	12,141.66 (4686.58)
Dr. Licenses	Fraction of drivers per household	0.1867 (.4415)
Avg. Comm.	Average time spent in commuting per day in minutes	67.58 (9.903)
Gas Cons.	Annual gasoline consumption (litres)	522.05 (223.208)
Gas Price	Gasoline price inclusive of taxes	30.12 (6.52)
N	Average Number of Households	6,051,016 (743,404)

"Pop. Dens." stands for population density, "Marr. Coup." stands for married couples, "PCI" stands for per capita income, "Dr. Licences" stand for fraction of state residents that hold the license to drive, and "Gas Cons." stands for gasoline consumption. Standard errors are reported in parenthesis.

Table 2.2: Age-wise deterioration factors for CO, HC and NOx in year 2000

Age Group	Vehicle Type	CO	HC	NOx
0-5	2w	1.64	1.18	0.06
5-10		4.89	3.37	0.06
10-15		5.77	3.485	0.07
0-5	4w	2.55	0.585	0.895
5-10		3.359	1.769	1.553
10-15		3.73	1.882	1.562

Source: Transport fuel quality for year 2005. Central pollution control board, Ministry of Environment and Forests, Government of India. Age-deterioration factors are defined as the ratio of average emissions per kilometer (EPK) from old vehicles to that of new vehicles in each age-group.

Table 2.3: Summary Statistics of Choice Variables

Choice Variables	4w-new	2w-new	4w-old	2w-old
Prop. choosing bundle i	0.038	0.127	0.056	0.194
Fuel Efficiency (KPL_i)	13.40	66.94	12.64	61.20
Emissions Rate (EPK_i, gm/km)	0.674	2.641	0.993	4.698
Annual Market Value (k_i)(Rs)	18034.86	1376.04	2386.07	139.59
Gasoline price per km (Rs/km)	5.32	2.49	6.46	2.06
Annual Vehicle tax (Rs)	361.68	91.17	262.46	87.00
Average age (years)	1.34	2.08	9.08	11.93
Vehicle Km Traveled (VKT)	10889	6275	9296	7235
Prop. in North	0.1006	0.1365	0.1132	0.2177
Prop. in South	0.0893	0.0677	0.1033	0.1039
Prop. in East	0.1149	0.0370	0.1191	0.0408
Prop. in West	0.1105	0.1004	0.1192	0.1362
Prop. of Hhs with education > high school	0.161	0.259	0.182	0.377
Prop. of Hhs owning homes	0.1637	0.1079	0.1956	0.1563
Prop. of Hhs with at least one income earner	0.376	0.271	0.194	0.446
Prop. of hhs with above average income	0.328	0.268	0.274	0.122
Prop. of Hhs in areas with above average pop. density	0.246	0.452	0.362	0.508
Prop. of Hhs > 15 years of age	0.105	0.457	0.128	0.662

Table 2.4: Regression of Fraction of State Residents that own Four-wheelers

	Coefficient	Robust S.E.	t-stat.	$P > \|t\|$
time trend (t)	0.28	0.18	1.56	0.122
Lnpci	0.55	0.068	8.09	0.945
cpi	-0.012	0.01	-1.21	0.261
α	0.548	0.346	1.58	0.117

This regression is a step in the direction to predict the number of four-wheelers that are being added to the vehicle fleet in each year and in each state. The regression includes 35 state dummies, and their interaction terms with t. Total number of observations = 183. R^2 = 0.7728. The column titled "Coefficients" represents the results of the regression.

Table 2.5: Regression of Fraction of State Residents that own Two-wheelers

	Coefficient	Robust S.E.	t-stat.	$P > \|t\|$
time trend (t)	0.034	0.013	2.62	0.011
lnpci	0.2744	0.170	1.61	0.953
cpi	0.001	0.008	0.125	0.925
α	0.681	0.261	2.61	0.011

This regression is a step in the direction to predict the number of two-wheelers that are being added to the vehicle fleet in each year and in each state. The regression includes 35 state dummies, and their interaction terms with t. Total number of observations = 183. R^2 = 0.8602. The column titled "Coefficients" represents the results of the regression.

Table 2.6: Estimated results of a regression of the Logarithm of Prices for Four-wheelers

	Coefficient	Robust S.E.	t-stat.	$P > \|t\|$
Dummy for North	1.0813	0.2372	4.56	0.000
Dummy for East	-0.9808	0.2662	-3.68	0.002
Dummy for West	-0.4484	0.1559	-2.88	0.01
time trend (t)	0.025	0.0035	7.14	0.000
cpi	0.0056	0.0042	1.35	0.194
sgdpgr-const	0.0012	0.0452	0.03	0.979
lnpcict	0.1289	0.5322	0.24	0.811
α	1.272	0.519	2.45	0.025

Regression includes 35 state dummies interacting with t. Total number of observations = 86. $R^2 = 0.9455$. The independent variables are as follows: Consumer Price index (cpi), growth rate of the state domestic product at constant 1993-94 price ($sgdpgr - const$), the logarithm of per capita income in constant 1993-94 prices ($lnpcict$), and a constant (α).

Table 2.7: Estimated results of a regression of the Logarithm of Prices for Two-wheelers

	Coefficient	Robust S.E.	t-stat.	$P > \|t\|$
Dummy for North	0.0725	0.0848	1.29	0.404
Dummy for East	-0.0032	0.0278	-2.11	0.010
Dummy for West	-0.0021	0.1624	-0.01	0.990
time trend (t)	0.0489	0.0067	7.32	0.000
cpi	0.0023	0.0007	3.43	0.003
sgdpgr-const	0.0152	0.0335	0.46	0.654
lnpcict	0.0905	0.1382	0.66	0.521
α	1.8836	0.738	1.61	0.000

Regression includes 35 state dummies interacting with t. Total number of observations = 86. $R^2 = 0.8866$. The independent variables are as follows: Consumer Price index (cpi), growth rate of the state domestic product at constant 1993-94 price ($sgdpgr - const$), the logarithm of per capita income in constant 1993-94 prices ($lnpcict$), and a constant (α).

Table 2.8: Estimated results of a regression of fuel-effficiency for new Four-Wheelers (KPL_{4wn}) on their emission rates (EPK_{4wn}), a time trend (t) and a constant (α)

	Coefficient	Robust S.E.	t-stat.	$P > \|t\|$
EPK_{4wn}	-0.4153	0.0345	-12.06	0.000
time trend (t)	0.0229	0.0039	5.89	0.000
α	-4.8453	0.7503	-5.53	0.000

Regression includes 35 state dummies, and their interaction terms with EPK. Total number of observations = 183. $R^2 = 0.8274$.

Table 2.9: Estimated results of a regression of fuel-effficiency for new Two-Wheelers (KPL_{2wn}) on their emission rates (EPK_{2wn}), a time trend (t) and a constant (α)

	Coefficient	Robust Standard Errors	t-statistic	$P > \|t\|$
EPK_{2wn}	-0.7624	0.1475	-5.17	0.000
time trend (t)	0.0151	0.0019	7.94	0.000
α	-6.451	0.7835	-8.23	0.000

Regression includes 35 state dummies, and their interaction terms with EPK. Total number of observations = 183. $R^2 = 0.8731$

Table 2.10: Estimation of Discrete Choice Model using GMM

Parameter	Estimates	S.E.	t-stat.	P-value
Family size (d1)	.3179	.0682	4.662	.000
Education (d2)	-.0390	.0126	-3.101	.002
Population Density (d3)	.8030	0.287	2.71	.005
Child (d4)	-1.576	.9598	-1.643	.091
Employment (d5)	.0618	.0208	2.972	.003
Share > age 15 (d6)	8.631	3.528	2.446	.014
Home owners (d7)	-2.139	0.507	-4.216	.000
North (E1)	.0086	.1509	0.056	.955
East (E2)	-.4029	.1158	-3.478	.001
West (E3)	.3018	.1197	2.521	.012
Income (B)	.9523	.1855	5.133	.000
Price per km for $4wn$ (α_{11})	-.4640	0.046	-7.214	.000
Price per km for $4wo$ (α_{12})	-.5047	0.123	-4.094	.000
Price per km for $2wn$ (α_{13})	-.3134	0.067	-6.924	.000
Price per km for $2wo$ (α_{14})	-.3360	0.030	-10.345	.000
Const. for choice $4wn$ (α_{01})	1.307	0.527	2.482	.011
Const. for choice $4wo$ (α_{02})	.9329	0.521	1.789	.001
Const. for choice $2wn$ (α_{03})	1.229	0.446	2.756	.007
Const. for choice $2wo$ (α_{04})	1.129	0.324	3.479	.004

Standard errors are computed from heteroscedastic-consistent matrix (Robust-white)

Table 2.11: Own and cross price elasticities for each discrete choice (the four columns) with respect to each petrol price (the four rows)

	4wn (1)	4wo (2)	2wn (3)	2wo (4)
Prices				
pr4wn (1)	-0.0112	0.0102	0.0102	0.0102
pr4wo (2)	0.0123	-0.3637	0.0123	0.0123
pr2wn (3)	0.0289	0.0289	-0.6985	0.0289
pr2wo (4)	0.1798	0.1798	0.1798	-0.8241

The first row identifies the four vehicle types as new four-wheelers ($4wn$), old four-wheelers ($4wo$), new two-wheelers ($2wn$), and old two-wheelers ($2wo$). The first column identifies the petrol price per kilometer of each of the above mentioned vehicle types in the same order.

Table 2.12: Own and cross price elasticities for each discrete choice (the four columns) with respect to each capital cost (the four rows) and income (last row)

	4wn (1)	4wo (2)	2wn (3)	2wo (4)	0 (5)
Capital Cost					
k-4wn	-0.0051	0.0038	0.0038	0.0038	0.0038
k-4wo	0.0017	-0.0164	0.0017	0.0017	0.0017
k-2wn	0.0022	0.0022	-0.0275	0.0022	0.0022
k-2wo	0.0012	0.0012	0.0012	-0.0938	0.0012
Income (y)	2.7688	1.6916	2.5682	1.0487	-0.9056

The first row identifies the four vehicle types as new four-wheelers ($4wn$), old four-wheelers ($4wo$), new two-wheelers ($2wn$), and old two-wheelers ($2wo$). The first four rows of the first column identify the prices of each of the above mentioned vehicle types in the same order.

Table 2.13: Estimation of VKT using Instrumental Variables Approach

Parameter	Estimates	S.E.	t-stat.	P-value
Family size (d1)	-0.2748	0.23	-1.2	[.232]
Education (d2)	0.1395	0.022	6.37	[.000]
Population Density (d3)	-0.0002	0.0001	-3.79	[.000]
Child (d4)	7.0514	12.6417	0.56	[.577]
Employment (d5)	0.0848	0.0785	1.08	[.28]
Share of households > age 15 (d6)	4.9434	11.2947	0.44	[.662]
Home owners (d7)	-5.5463	1.4066	-3.94	[.000]
North (E1)	-0.3918	0.3815	-1.03	[.305]
East (E2)	-2.4769	0.3344	-7.41	[.000]
West (E3)	-0.3582	0.3132	-1.14	[.253]
Income (B)	0.2896	0.0677	4.27	[.000]
Price per km for $4wn$ (α_{11})	-0.5225	0.2778	-4.36	[.000]
Price per km for $4wo$ (α_{12})	-4.8583	0.7100	-5.24	[.000]
Price per km for $2wn$ (α_{13})	-3.7200	1.0511	-4.62	[.000]
Price per km for $2wo$ (α_{14})	-1.2125	0.0123	-42.6	[.000]
Constant (α_0)	2.6152	1.5943	1.642	[.052]

The title of the third column stands for Standard Error (S.E.)

Table 2.14: Elasticities for Continuous Choice

Elasticities for VKT with respect to:	Values
Petrol Cost per km of choice $4wn$	-1.78351
Petrol Cost per km of choice $4wo$	-5.1532
Petrol Cost per km of Choice $2wn$	-0.3986
Petrol Cost per km of Choice $2wo$	-0.7803
Income	0.22399
Capital Cost of choice $4wn$	-0.0138
Capital Cost of choice $4wo$	-0.0199
Capital cost of Choice $2wn$	-0.0238
Capital cost of Choice $2wo$	-0.0947

All the elasticities are evaluated at the mean values of the variables.

Table 2.15: Comparison of Tax Instruments

Change in p_i (Rs/km)	0	0.04	0.08	0.12	...	0.70	0.74	0.78
t_g (Rs/km)	0	1.51	3.01	4.52	...	27.11	28.61	30.12
t_e (Rs/km)	0	0.02	0.03	0.05	...	0.31	0.33	0.35
t_d (Rs/km)	0	0.04	0.08	0.12	...	0.70	0.74	0.78

Chapter 3

Welfare Effects of Scrappage Subsidies in the Presence of Asymmetric Information

The purpose of this paper is to evaluate the effects of accelerated vehicle retirement programs, also known as scrappage programs in the presence of information asymmetry in the used car market. I also calculate the optimal subsidy rate and compare it to the rate set by current scrappage programs, and finally I analyze the welfare effects of such a subsidy.

Scrappage programs are often adopted to reduce the number of highly polluting, used vehicles on the road. In the presence of prohibitively expensive infrastructure to measure emissions, policy-makers cannot observe the pollution levels of cars. However, since car owners have preferences over car quality, the government has some information about how used cars of different quality levels are allocated amongst car buyers. To get around the problem of unobservable emissions, the government aims to remove the majority of polluting cars by targeting low-quality used cars by using information on which car owners get cars of which quality. A scrappage program based on this principle is effective only if car quality and emissions are highly correlated which might not be the case. In other words, if low-quality cars are the ones that are more likely to be the most polluting, then current scrappage programs will succeed in removing most of the polluting cars from the road. However, if a substantial fraction of the high-quality used cars are the ones contributing to air pollution, then the program will not reduce pollution significantly.

Since emissions is unobservable, scrappage programs are voluntary. Individuals are offered a fixed dollar amount to scrap cars that are older than a certain age. The underlying principle of current scrappage programs is that a car's quality or value is negatively correlated to the amount of annual emissions it generates. If a car owner is assumed to have low utility from a low-quality car that is highly polluting, then a sufficient compensation offer would successfully scrap the high-emitting vehicles due to the self-selection mechanism. However, high-quality used cars can be polluting as well, albeit with a lower probability than their low-quality counterparts. Hence, a subsidy that seeks to scrap only the low-quality used cars might not be effective in improving air quality if there exist a substantial proportion of highly polluting high-quality used cars in the fleet.

Moreover, another factor besides the quality of the car affects the scrappage decision. Car owners have different preferences for the quality of cars. A car owner's utility from a car depends on both the quality of the car and the owner's preference for the quality. The allocation of cars to owners with different preferences matters. The scrappage program will scrap the highly polluting cars with a minimum subsidy only if the automobile market allocates low quality cars to those with a low preference for car quality, and assigns high quality cars to those with a high preference.

The problem that occurs in achieving an effective subsidy is that the resale market does not always allocate the poorest quality cars to the owners with the lowest preferences for quality. This inefficiency in allocation results from adverse selection in the second hand market. Quality of cars is observable to its sellers, but not to the buyers. This information asymmetry has a significant effect on the amount of the subsidy required to scrap the highly polluting used cars. My paper shows that the amount of the subsidy needed to scrap the highly polluting cars rises with information asymmetry in the second-hand market for private automobiles.

Scrappage programs have been popular in Europe, and in few geographically-localized regions of Canada and the United States. Most European Union (EU) countries offer country-wide subsidies. France, Greece, Hungary, Ireland, Italy and Spain required scrapped cars to be replaced by a new vehicle. Other countries such as Denmark, Norway, the United States and Canada did not impose any such constraints on the type of replacement vehicle.[1] In my paper I focus my analysis on the effects of an unconstrained subsidy. Little work has been done to identify the implications of such a subsidy on the automobile market as well as on emissions.[2] Recently the possibility of expanding such programs has sparked a debate on their effects on the car market. Adda and Cooper

[1]See Hahn (1995), EPA (1998), and European Conference of Ministers of Transport (1999) for a comprehensive description of the different scrappage subsidy programs in the United States and Europe.

[2]See Alberini et al. (1995, 1996) for empirical work on scrappage programs.

(2000) use a replacement-demand model with a competitive primary market to examine the effects of a scrappage subsidy that required the replacement vehicle to be new. Since their main interest is to study the impacts of such a policy on new car sales, they do not include an active market for used cars. More recently Esteban (2005) also analyzes an unconstrained scrappage subsidy in the presence of monopoly distortions in the new car market. She, however, incorporates a used market without information asymmetry. Thus, my contribution to the literature is to examine the implications of such a program in a theoretical framework with information asymmetry.

To evaluate the effects of information asymmetry in the second hand market on the scrappage subsidy, I use a simplified version of Hendel and Lizzeri's (1999) model of adverse selection. The model is a dynamic framework where agents have heterogeneous preferences for car quality. However, the quality of a used car in my paper is discrete. I also correlate car quality with emission level in order to study the environmental implications of the scrappage policy. I first examine the case where used cars' qualities are observable to all traders, and used cars of every quality have a unique price. This second-hand market allocates cars efficiently amongst heterogeneous buyers according to their preferences for car quality. I use this case as a benchmark to examine how adverse selection impacts the level of the subsidy as well it's implementation.

Next I examine the case where quality is not observable, and used cars are priced according to the average quality of traded used cars in the market.

In this case, a low quality car could be owned by a consumer with a preference for relatively high quality. To scrap the highly polluting poor quality cars, the subsidy must now be larger than the benchmark to compensate the high preference owner. If the subsidy is sufficiently higher, some car owners would also be willing to scrap their good quality cars. Thus, in the presence of information asymmetry the program subsidizes the scrapping of the highly polluting cars at a higher rate, and could potentially be paying for the scrappage of some good quality cars. My focus is to evaluate the extent to which information asymmetry in the resale market affects the subsidy and how the subsidy in turn affects allocation of cars in the used car market. One key result is that in the presence of adverse selection a subsidy that maintains an active resale market unambiguously makes all types of consumers better off. However, if this option of implementing the subsidy does not exist, then the only other way to induce effective scrappage in my framework is to shut down the used car market. My welfare implications suggest that it might be better not to do anything rather than have a scrappage program such as the latter. Finally, the optimal subsidy for scrappage is lower than the subsidy currently used to scrap all low-quality used cars.

The paper is organized as follows: Section 3.1 describes the model. Section 3.2 analyzes the model when quality is uncertain but observable, with and without a scrappage program. Section 3.3 analyzes the case of information asymmetry with and without a subsidy. Section 3.4 presents a numerical solution to the model, and finally Section 3.5 concludes.

3.1 Model

I consider a discrete time, infinite-horizon economy in which individuals can choose to consume either a new car, or a used car. I also assume that a unit mass of infinitely-lived car owners are born at the beginning of time, and that no new consumers are added to the economy. Individuals purchase cars because they value the services from a car of quality, w_t. Agents' preferences for car quality are heterogenous and are denoted by θ, which is distributed according to a cumulative distribution function, F. I assume that F is strictly increasing and continuous on the interval $[\underline{\theta}, \overline{\theta}]$. Used cars are polluting and add to the total quantity of emissions, denoted by Q_E. At time t, a car owner of type θ pays a price $P_{w,t}$ for a car of quality w_t and enjoys a utility flow from it given by the following quasi-linear function:

$$U(q_t, \theta) = \theta w_t - P_{w,t} - \mu Q_E \tag{3.1}$$

where μ is the marginal environmental damage from emissions.[3] I assume that all consumers are negatively affected by worsening air quality, but each car owner is a very small share of the entire market and so ignores the effects of his or her own actions on total emissions. All consumers at any time t demand at most one car, and all have a discount factor of δ.

New cars are assumed to generate zero level of pollution. Thus, emissions are generated by low- and high-quality used cars. Emissions generated by used cars can either be high or low. I simplify to assume that low-emission

[3] All agents have identical income, y, that I normalize to zero.

levels are zero. Let high-quality used cars be polluting with probability α, while low-quality used cars are polluting with probability β. I assume that $\beta > \alpha$, implying that low-quality used cars are more likely to be polluting than high-quality used cars, and these probabilities are not affected by the actions of the car owners. Thus, the aggregate quantity of emissions generated from used cars is given by the following function:

$$Q_E = \beta q_l + \alpha q_h \tag{3.2}$$

where q_l is the quantity of low-quality used cars, and q_h is the quantity of high-quality used cars. I assume that each car generates a constant amount of emissions, and for simplicity I set that constant equal to one. Thus, the total amount of emissions generated from low-quality used cars is equal to its proportion in the fleet.

Cars last for two periods. A car is new in the first period, and used in the second. New cars may be sold to someone else at the end of the first period, who then uses it for one more period before its value falls to zero at the end of the second period. Car quality is discrete, and can be of five types: new cars with no emissions, a low-quality used car with no emissions, a low-quality used car with high emissions, a high-quality used car with no emissions, and a high-quality used car with high emissions. Since emissions from cars are not observed in the market, car prices are not determined by it. Hence, in reality the proportion of each type of used car is a weighted sum of its high and low emissions counterparts. However, since emission levels are unobservable, only cars of different qualities can be observed. Hence, from the perspective of the market cars are of three types: a new car (v), a low quality used car (w_l), or a high-quality used car (w_h). All new cars have the same quality level. Quality realizations of used cars is random, but since the realization of v is not relevant to my analysis, I fix v to be equal to 1. The quality of a used car is realized in the second period, and is unobservable to the buyers in the used car market. A used car turns out to be of high quality with probability p, and that of low quality with probability $(1-p)$. Moreover, $w_h \leq v$, so that a used car always depreciates in quality.

The government's goal under current scrappage programs is to reduce pollution by getting rid of the high-emissions used cars. However, emissions of cars cannot be observed at reasonable cost, but the government does have some information on how cars of different quality are distributed across car buyers. The policy then uses this information on car quality distribution to reduce pollution by targeting low-quality used cars, working under the assumption that these cars are more likely than high-quality used cars to be polluting. For this purpose, the policy offers a subsidy, S for voluntary scrappage of all such cars. However, this policy might not get rid of the most polluting cars even in the absence of information asymmetry in the second-hand market as shown below. Moreover, information asymmetry makes the program more costly to scrap even the poor quality used cars. Consumers decide whether or not to purchase a car and also choose the type of car based on their preference for car quality and its price.

For notation, the paper follows the convention of using a superscript to denote the case being examined and a subscript either to refer to the type of consumer, or to the type of car. The analysis examines the following five categories: o stands for the observable quality case without a subsidy, os stands for the observable case with a subsidy, i stands for information asymmetry without a scrappage program, is denotes information asymmetry with a subsidy that eliminates the resale market for cars, and finally isr is the case with information asymmetry in the presence of a subsidy that retains a second-hand market for used cars.

A subscript to a preference parameter, θ, refers to the type of consumer, and can be one of the following: n stands for owners who purchase new cars every period, h stands for buyers of high-quality used cars, l stands for low-quality buyers, u denotes the used car buyer in the unobservable case, nk is new car owner who keeps cars of high quality, and finally a no subscript denotes consumers who choose the outside option of not purchasing a car. Furthermore, a subscript on quality or price refers to the type of car, and can be one of the following: n stands for new, h stands for high-quality used car, l stands for low-quality used car, and u stands for a used car.

I ignore the effects of market structure in the new car market and focus on the allocation of used cars and new cars amongst the buyers and sellers in the presence of information asymmetry with and without a scrappage subsidy. I assume that the price of new cars, P_n is exogenously given, and all endogenous variables are solved in terms of it. I also focus my attention on steady-state allocations. In sections 3.2 and 3.3 I examine how the scrappage subsidy changes in the presence of information asymmetry relative to the benchmark case when quality is observable.

3.2 Equilibrium with Observable Quality

I first present two benchmark cases with no asymmetric information, one with and the other without a scrappage subsidy. I use these results to compare the effects of adverse selection on the allocation of low-quality used cars and hence on emissions, as well as how it affects the effective subsidy level.

3.2.1 No Scrappage Subsidy

Here I consider the automobile market when quality of used cars is observable to both buyers and sellers, but the realizations of used car quality are non-deterministic. In other words, when a new car turns used in the second period, it could be either of high- or low-quality, but which it will be is not known when a new car is bought. This makes the resale value of a new car uncertain at the time of purchase. Moreover, the used car buyer always knows the quality of the car at the time of purchase. The used car market in this case uniquely determines a price for each type of used car. The price of a used car of quality w_l is given by P_l^o, while that of a car of quality of w_h is given by P_h^o. I solve for the equilibrium allocations of both types of used cars and that of new cars, as well the prices of each used car type.

Following Hendel and Lizzeri(1999), four types of agents exist in this equilibrium. Types in $[\underline{\theta}, \theta_l^o]$ do not buy a car at all, types in $[\theta_l^o, \theta_h^o]$ purchase a low-quality used car at the end of every period, types in $[\theta_h^o, \theta_n^o]$ purchase a high-quality used car at the end of every period, and types in $[\theta_n^o, \overline{\theta}]$ purchase a new car and trade it when it turns used after one period. Appendix D shows that θ is increasing in w. This implies that consumers with higher preferences for quality choose the high-quality cars, while those with lower preferences choose the low-quality cars. Thus, the secondary market correctly matches the "right" car to the "right" customer. I now characterize the behavior of each of these types.

(1) Types in $[\theta_n^o, \overline{\theta}]$: These consumers purchase a new car, keeps it for one period and then resells it. They purchase a new car to enjoy the higher services from it. The total demand for new cars is given by $F(\overline{\theta}) - F(\theta_n^o)$. The lifetime utility of an infinitely-lived typical car owner of this type is:

$$V_n^o(\theta) = \frac{\theta - P_n + \delta E(P(w)) - \mu Q_E}{1 - \delta} \tag{3.3}$$

where $E(P(w)) = pP_h^o + (1-p)P_l^o$ is the expected price of a used car and reflects the quality uncertainty of the used car to this car owner at the time he or she purchases a new car.

(2) Types in $[\theta_h^o, \theta_n^o]$: These car owners have valuations for car quality that are high enough to pay for the higher price of good quality used cars relative to that of low quality used cars, but are not high enough to

purchase new cars. The total demand for high quality used cars is: $F(\theta_n^o) - F(\theta_h^o)$. The lifetime utility of is:

$$V_h^o(\theta) = \frac{\theta w_h - P_h^o - \mu Q_E}{1-\delta} \tag{3.4}$$

(3) Types in $[\theta_l^o, \theta_h^o]$: Marginal consumer θ_l^o is also the lowest type who purchases a car. Consumers with valuations lower than θ_l^o prefer the outside option of not purchasing a car at any date t. Types with valuations greater than θ_l^o prefer purchasing a low-quality car than not driving one at all. The lifetime utility of is:

$$V_l^o(\theta) = \frac{\theta w_l - P_l^o - \mu Q_E}{1-\delta} \tag{3.5}$$

(4) Types in $[\underline{\theta}, \theta_l^o]$: These consumers get a utility of $\frac{-\mu Q_E}{1-\delta}$ every period.

The valuations of the three marginal consumers θ_n^0, θ_h^o, and θ_l^o are determined by their respective indifference equations. Type θ_n^o is indifferent between purchasing a new car and a used car of good quality. Type θ_h^o is indifferent between purchasing a used car of good quality and that of poor quality, while type θ_l^o is indifferent between buying a used car of poor quality and not purchasing a car at all. These conditions are summarized in the following three equations:

$$
\begin{aligned}
V_l^o(\theta_l^o) &= \frac{\theta_l^o w_l - P_l^o - \mu Q_E^o}{1-\delta} = \frac{-\mu Q_E^o}{1-\delta} \Rightarrow P_l^o = \theta_l^o w_l && (3.6)\\
V_h^o(\theta_h^o) &= V_l^o(\theta_h^o) \Rightarrow \frac{\theta_h^o w_h - P_h^o - \mu Q_E^o}{1-\delta} = \frac{\theta_h^o w_l - P_l^o - \mu Q_E^o}{1-\delta} \\
&\Rightarrow P_h^o = \theta_h^o(w_h - w_l) + P_l^o && (3.7)\\
V_n^o(\theta_n^o) &= V_h^o(\theta_n^o) \Rightarrow \frac{\theta_n^o - P_n + \delta E(P(w)) - \mu Q_E^o}{1-\delta} = \frac{\theta_n^o w_h - P_h^o - \mu Q_E^o}{1-\delta} \\
&\Rightarrow \theta_n^o(1-w_h) + \delta E(P(w)) + P_h^o = P_n^o && (3.8)
\end{aligned}
$$

Equation 3.7 implies that the difference between the prices of a high- and low-quality used car is exactly equal to the additional benefit offered by a high-quality used car.

Finally, the prices of both types of used cars are determined by their respective market clearing conditions. That is, if the market for high quality used cars is to clear, it must be true that their supply given by $p(F(\overline{\theta})-F(\theta_n^o))$, equals their demand, given by $F(\theta_n^o) - F(\theta_h^o)$. Similarly, the supply of low-quality used cars, given by $(1-p)(F(\overline{\theta}) - F(\theta_n^o))$, must equal their demand, given by $F(\theta_h^o) - F(\theta_l^o)$. Thus, the market clearing conditions for both types of used cars are as follows:

$$
\begin{aligned}
p(F(\overline{\theta}) - F(\theta_n^o)) &= F(\theta_n^o) - F(\theta_h^o) && (3.9)\\
(1-p)(F(\overline{\theta}) - F(\theta_n^o)) &= F(\theta_h^o) - F(\theta_l^o) && (3.10)\\
& && (3.11)
\end{aligned}
$$

The quantity of emissions generated is a function of the proportion of highly polluting used cars in the market that could be of high- or of low-quality.

In section 3.4, I use the equations 3.6, 3.7 3.8, 3.9, and 3.10 to numerically calculate the values of my endogenous variables θ_n^o, θ_h^o, θ_l^o, P_h^o and P_l^o in terms of the price of new cars. When quality is observable, the market for used cars perfectly matches consumer preferences to car quality.

3.2.2 With Subsidy to Scrap all Low-quality used cars

In this section I analyze how the allocation of used cars changes in the presence of a subsidy, S^{os}, offered to car owners to induce them to scrap their low-quality used cars. I also determine the minimum level of the subsidy required to scrap all the low-quality used cars, and compare it to the price of used cars in the environment without the subsidy. In my model, the low-quality used cars are not necessarily the most polluting. Hence this subsidy might not be effective in reducing pollution if there exist a substantial number of high-quality cars that are also polluting. Note that a subsidy that induces scrappage of all the low-quality used cars must be such that no agent has the incentive to participate in the second hand market for this type of car. For this to occur, the subsidy must compensate the highest type that purchases a low-quality used car in this set-up (θ_h^o). Since the used car market in the observable case perfectly matches the car to its owner, it implies that θ_h^o is the lowest types to ever purchase a low-quality used car. Hence, the level of S^{os} is the lowest at which the government achieves its goal. Since all poor-quality used cars are scrapped, Q_E^{os} is the proportion of high-quality used cars that are polluting.

Given the above condition on the scrappage subsidy, I have three types of agents in the market: types in $[\underline{\theta}, \theta_h^{os}]$ do not purchase a car, types in $[\theta_h^{os}, \theta_n^{os}]$ purchase a high-quality used car, and types in $[\theta_n^{os}, \overline{\theta}]$ purchase a new car, then sells it at the end of first period if the used car turns out to be of high-quality, but scraps it if it turns out to be of low-quality. Let P_h^{os} be the price of high-quality used cars.

(1) Types in $[\theta_n^{os}, \overline{\theta}]$: The lifetime utility of these infinitely-lived consumers is given as:

$$V_n^{os}(\theta) = \frac{\theta - P_n + \delta[E(P(w))]}{1-\delta} \tag{3.12}$$

where $E(P(w)) = pP_h^{os} + (1-p)S^{os}$ is the price that the new car buyer expects to receive for his or her used car, and Q_E^{os} is the quantity of emissions generated. If the subsidy is effective in scrapping all the low quality used cars, then $Q_E^{os} < Q_E^{o}$.

(2) Types in $[\theta_h^{os}, \theta_n^{os}]$: Their lifetime utility is given as follows:

$$V_h^{os}(\theta) = \frac{\theta w_h - P_h^{os}}{1-\delta} \tag{3.13}$$

(3) Types in $[\underline{\theta}, \theta_h^{os}]$: Their lifetime utility is zero in the presence of the subsidy.

Thus, if the subsidy is 100 percent effective, it eliminates the market for low-quality used cars. In section 3.4 I compute an example of how the prior owners of low-quality used car buyers change their behavior in the presence of the subsidy. The condition on the subsidy required to support the above equilibrium allocation is given below.

The two marginal consumers, θ_n^{os}, and θ_h^{os} are determined by their indifference conditions. The marginal consumer, θ_n^{os} is indifferent between buying a new car and a high-quality used car. The marginal consumer, θ_h^{os}, is indifferent between purchasing a high-quality used car and not purchasing a car at all. These two conditions are:

$$\begin{aligned}
V_n^{os}(\theta_n^{os}) &= V_h^{os}(\theta_n^{os}) \Rightarrow \frac{\theta_n^{os} - P_n + \delta[E(P(w))] - \mu Q_E^{os}}{1-\delta} = \frac{\theta_n^{os} w_h - P_h^{os} - \mu Q_E^{os}}{1-\delta} \\
&\Rightarrow \theta_n^{os}(1-w_h) = P_n - P_h^{os}(1-\delta p) - (1-p)S \\
V_h^{os}(\theta_h^{os}) &= V^{os}(\theta_h^{os}) \Rightarrow \frac{\theta_h^{os} w_h - P_h^{os} - \mu Q_E^{os}}{1-\delta} = -\frac{\mu Q_E^{os}}{1-\delta} \\
&\Rightarrow \theta_h^{os} w_h = P_h^{os}
\end{aligned} \tag{3.14}$$

The subsidy that supports the above equilibrium allocation must be such that it makes the consumer with the highest valuation amongst the no car buyers prefer not buying a car than to purchase a used car of low quality. In other words, S^{os}, must be such that $\theta_h^{os} w_l - S^{os} \leq 0$. To achieve this allocation at least cost, the government picks the lowest level of the subsidy. Thus, $S^{os} = \theta_h^{os} w_l$.

Finally, the price of high quality used cars is determined by the market clearing condition where the demand for old high quality cars equals its supply.

This is given as follows:

$$F(\theta_n^{os}) - F(\theta_h^{os}) = p[F(\overline{\theta}) - F(\theta_n^{os})] \tag{3.15}$$

Thus, equations 3.14, 3.15 and the equation for the minimum subsidy level determine the endogenous variables in this set up. These equations are used in the Numerical Section to compare how the market allocation with the scrappage subsidy differs from that without, and how the subsidy affects the welfare of the different types of consumers.

3.2.3 Optimal Subsidy rate when Car quality is observable

In this section, I solve for the optimal subsidy rate and compare it to the subsidy needed to scrap all low-quality used cars. I express all endogenous variables as functions of the subsidy rate and then plug these functions into the social welfare function. Next I differentiate the welfare function and set it equal to zero to solve for the optimal subsidy rate, S_o^* (details are shown in the Appendix). The scrappage policy in place assumes that to reduce pollution from existing cars, all low-quality used cars must be scrapped. However, the optimal number for scrappage is at the point where the benefits from scrappage in terms of lower emissions is equal to the cost of scrappage in terms of the subsidy as well as the loss in utility from substitution effects of the policy. Hence, here I have some low-quality used car buyers that keep the low-quality car as the subsidy might not be high enough, while some others scrap it.

Let θ be distributed uniformly between [0,1]. Let the marginal types be: θ^*_{ls}, θ^*_{lk}, θ^*_h, θ^*_n, where types in $[0, \theta^*_{ls}]$ purchase no car, types in $[\theta^*_{ls}, \theta^*_{lk}]$ purchase a low-quality used car, and scrap it, types in $[\theta^*_{lk}, \theta^*_h]$ buy low-quality used cars and keep it, types in $[\theta^*_h, \theta^*_n]$ purchase high-quality used cars, and finally types in $[\theta^*_n, \overline{\theta}]$ purchase new cars every period and resell the used cars in the second hand market.

The endogenous variables are: $(\theta^*_{ls}, \theta^*_{lk}, \theta^*_h, \theta^*_n, P^*_l, P^*_h)$. The exogenous variable is S, whose optimal rate I want to solve for from the welfare equation. The indifference equations for each marginal type are:

$$\theta^*_n - P_n + \delta[pP^*_h + (1-p)P^*_l] = \theta^*_n w_h - P^*_h \tag{3.16}$$

$$\theta^*_h w_h - P^*_h = \theta^*_h w_l - P^*_l \tag{3.17}$$

$$S = \theta^*_{lk} w_l \tag{3.18}$$

$$P^*_l = S \tag{3.19}$$

$$p(1-\theta^*_n) = \theta^*_n - \theta^*_h \tag{3.20}$$

$$(1-p)(1-\theta^*_n) = \theta^*_h - \theta^*_{ls} \tag{3.21}$$

The subsidy rate is equal to the low-quality used car price. Thus, when selling a low-quality used car, the seller is indifferent between re-selling in the used car market and scrapping. I assume that the seller re-sells in the case of indifference between these two decisions. The above system of equations is solved and each endogenous variable is expressed in terms of the subsidy rate, S. I substitute each of these reduced form solutions for the endogenous variables into the social welfare function given as follows:

$$
\begin{aligned}
W(S) &= \int_{\theta_n^*(S)}^{1} V_n(\theta,S)d\theta + \int_{\theta_h^*(S)}^{\theta_n^*(S)} V_h(\theta,S)d\theta + \int_{\theta_{lk}^*(S)}^{\theta_h^*(S)} V_{lk}(\theta,S)d\theta \\
&+ \int_{\theta_{ls}^*(S)}^{\theta_{lk}^*(S)} V_{ls}(\theta,S)d\theta + \int_{0}^{\theta_{ls}^*(S)} V_0(\theta)d\theta - \int_{\theta_{ls}^*}^{\theta_{lk}^*} \frac{S}{1-\delta}d\theta - \frac{\mu Q_E(\theta_h(S)-\theta_{lk}(S))}{1-\delta} \\
&= \int_{\theta_n^*(S)}^{1} \frac{\theta - P_n + \delta(pP_h^* + (1-p)P_l^*)}{1-\delta}d\theta + \int_{\theta_h^*(S)}^{\theta_n^*(S)} \frac{\theta w_h - P_h^*}{1-\delta}d\theta \\
&+ \int_{\theta_{lk}^*(S)}^{\theta_h^*(S)} \frac{\theta w_l - P_l^*}{1-\delta}d\theta + \int_{\theta_{ls}^*(S)}^{\theta_{lk}^*(S)} \frac{S - P_l^*}{1-\delta}d\theta \\
&- \frac{\mu Q_E(\alpha(\theta_h^*(S)-\theta_{lk}^*(S))) + \beta(\theta_n^*(S)-\theta_h^*(S))}{1-\delta} - \int_{\theta_{ls}^*}^{\theta_{lk}^*} \frac{S}{1-\delta}d\theta
\end{aligned}
\tag{3.22}
$$

Differentiating the above welfare equation with respect to S and setting it equal to zero solves for the optimal subsidy, S_o^* in the observable case. This subsidy is calculated for a given set of parameters in the Numerical Section below.

3.3 Equilibrium when quality is not observable

3.3.1 No Scrappage Subsidy

In this section I examine the case where used car quality is observed only by the seller and not by the buyer. I use the results here to contrast the allocation and prices of used cars obtained to that under the observable case without a subsidy in Section 3.2.1. Due to this information asymmetry used car buyers have lower expectation regarding the average quality of the traded used car. A high-quality used car is now priced according to this average expectation. Since all used cars in this case are sold at one price, the price of the good quality cars is now lower than it was in the observable case without the subsidy, while that of the bad quality ones is higher. This in turn distorts the behavior of some of the sellers. Some of the consumers who were previously purchasing a new car and reselling the used car after one period do not continue to do so. Instead, now they keep their used car if it turns out to be of high quality, and sells it only if the it turns out to be of low quality. For these types, the benefit of purchasing a new car is less than the utility lost from receiving a lower price for their high-quality used car at the time of resale. Thus, these types now enter the new car market less often. Information asymmetry drives out some, but not all of the good cars from the resale market and hence raises the fraction of used cars that are of low-quality. Thus, the quantity of emissions generated in the presence of adverse selection, Q_E^i is greater than that generated in its absence, Q_E^o.

The highest valuation consumers continue to purchase a new car and sell it when it turns used at the end of one period, even if the car turns out to be of high quality. This is because their utility gain from enjoying the higher services of a new car is greater than the loss in value from selling their used car at a lower price in the used car market.[4] In equilibrium, types in $[\underline{\theta}, \theta_u^i]$ do not purchase a car, types in $[\theta_u^i, \theta_{nk}^i]$ purchase a used car every period, types in $[\theta_{nk}^i, \theta_n^i]$ purchase a new car, keep the used car if it is of good quality and

[4]This is different from the Hendel and Lizzeri (1999) result, and in my paper it is due to my definition of new and used cars.

trades if it turns out to be of low-quality, and finally types in $[\theta_n^i, \overline{\theta}]$ purchase a new car and trade in the used car at the end of the first period regardless of quality. The behavior of these four types of consumers are characterized as follows:

(1) Types in $[\theta_n^i, \overline{\theta}]$: The lifetime utility of these highest valuation consumers is:

$$V_n^i = \frac{\theta - P_n + \delta P_u^i - \mu Q_E^i}{1 - \delta} \tag{3.23}$$

where P_u^i is the price of a used car, and Q_E^i is the quantity of emissions produced under information asymmetry.

(2) Types in $[\theta_{nk}^i, \theta_n^i]$: The behavior of these consumers is the distortion created by adverse selection. These consumers would have ideally liked to purchase new cars at the end of every period, but their valuations are not high enough to compensate them for the loss in value of their good-quality used cars. Their lifetime utility is:

$$\begin{aligned} V_{nk}^i &= \theta - P_n - \mu Q_E^i + \delta(1-p)[P_u^i + V_{nk}^i] + \delta p[\theta w_h + \delta V_{nk}^i] \\ \Rightarrow V_{nk}^i &= \frac{\theta(1 + \delta p w_h) - \mu Q_E^i + \delta(1-p)P_u^i - P_n^i}{1 - \delta(1-p) - \delta^2 p} \end{aligned} \tag{3.24}$$

(3) Types in $[\theta_u^i, \theta_{nk}^i]$: At the time of purchase, these types no longer know what quality car they will be driving. Thus, they form expectations about the quality of the traded used car, denoted by w_u^i, and in equilibrium this is equal to the average quality of the used cars being supplied.

The lifetime utility of these consumers is given as follows:

$$V_u^i = \frac{\theta w_u^i - P_u^i - \mu Q_E^i}{1-\delta} \tag{3.25}$$

Here I assume that agents can trade only once in the used car market. This implies that owners of low-quality used cars cannot resell in the second-hand market, once they learn the quality of their purchase.

(4) Types in $[\underline{\theta}, \theta_u^i]$: Their lifetime utility is:

$$V_0^i = -\frac{\mu Q_E^i}{1-\delta} \tag{3.26}$$

The three marginal consumers in the model with adverse selection are θ_n^i, θ_{nk}^i, and θ_u^i. Type θ_n^i is indifferent between purchasing a new car at the end of a period and keeping the used car if it turns out to be of good quality. Type θ_{nk}^i is indifferent between purchasing a new car and keeping the good quality used car, or buying a used car every period. Finally, type θ_u^i is indifferent between purchasing a used car and not purchasing a car at all. These conditions are:

$$\begin{aligned}
V_n^i(\theta_n^i) &= V_{nk}^i(\theta_n) \Rightarrow \frac{\theta_n^i - P_n + \delta P_u^i}{1-\delta} = \frac{\theta_n^i(1+\delta p w_h) + \delta(1-p)P_u - P_n}{1-\delta(1-p)-\delta^2 p} \\
V_{nk}^i(\theta_{nk}^i) &= V_u^i(\theta_{nk}^i) \Rightarrow \frac{\theta_{nk}^i(1+\delta p w_h) + \delta(1-p)P_u^i - P_n}{1-\delta(1-p)-\delta^2 p} = \frac{\theta_{nk}^i w_u^i - P_u^i}{1-\delta} \\
V_u^i(\theta_u^i) &= V_0^i(\theta_u^i) \Rightarrow \theta_u^i w_u^i = P_u^i
\end{aligned} \tag{3.27}$$

The price of used cars in this framework is determined by the market clearing condition for used cars where the demand for used cars equals their supply. This is given as follows:

$$F(\theta_{nk}) - F(\theta_u) = F(\overline{\theta}) - F(\theta_n) + (1-p)[F(\theta_n) - F(\theta_{nk})] \tag{3.28}$$

Note that in the presence of adverse selection, only one market exists for both the good and bad qualities of used cars. Finally, the last equilibrium condition defines expectations of the used car buyer as:

$$w_u^i = \frac{(1-p)[F(\theta_n^i) - F(\theta_{nk}^i)]w_l + [F(\overline{\theta}) - F(\theta_n^i)](pw_h + (1-p)w_l)}{F(\overline{\theta}) - F(\theta_n^i) + (1-p)[F(\theta_n^i) - F(\theta_{nk}^i)]} \tag{3.29}$$

This ratio expresses the average quality of the used car being traded as a proportion of the total fraction of used cars in the market. In the numerical section, I use equations 3.27, 3.28 and 3.29 to determine the effects of adverse selection on the allocations of low-quality used cars, and hence on emissions, and then compare the results to the observable case without the subsidy.

3.3.2 With a Subsidy to Scrap all Low-quality Used cars

When the government offers a subsidy to induce individuals to scrap their cars, I can have one of the two following cases: either a subsidy that maintains an active resale market, or one that does not. In Section 3.4, I characterize the parameter space that determines which of these two cases exists. I also discuss the effects on welfare in each case, and indicate which is a better equilibrium to achieve. I now discuss the behavior of consumers when the subsidy is such that no resale market exists.

3.3.3 Case 1: Subsidy with no Resale Market

In this section the subsidy is such that the used car sellers prefer to scrap their cars rather than resell them in the market. Two types of consumers exist in this case. The highest valuation consumers continue to purchase a new car every period and to scrap the used car regardless of its quality. Lower valuation consumers enter the new car market less often, keep their used car if it is of good quality, and scrap it if it turns out to be of poor quality. In equilibrium, types in $[\underline{\theta}, \theta_{nk}^{is}]$ do not purchase a car, types in $[\theta_{nk}^{is}, \theta_n^{is}]$ purchase new cars, keep it if it is of good quality and scrap it if it is of poor quality, and types in $[\theta_n^{is}, \overline{\theta}]$ purchase a new car and scrap it when it turns used in the next period. The behavior of each of these types is characterized below:

(a) Types in $[\theta_n^{is}, \overline{\theta}]$: These consumers scrap a used car, regardless of whether it is of high- or low-quality. Thus, a subsidy in this case pays for the scrappage of some good used cars along with the polluting ones. The lifetime utility of a typical consumer of this type is:

$$V_n^{is} = \frac{\theta - P_n + \delta S^{is}}{1 - \delta} \tag{3.30}$$

where S^{is} is the scrappage subsidy with information asymmetry and no resale market. Since all poor-quality cars are scrapped, the quantity of emissions is zero.

(b) Types in $[\theta_{nk}^{is}, \theta_n^{is}]$: Their lifetime utility is given as follows:

$$V_{nk}^{is} = \frac{\theta - P_n + \delta(1-p)S^{is} + \delta p \theta w_h}{1 - \delta(1-p) - \delta^2 p} \tag{3.31}$$

If the subsidy is high enough, these types will also scrap their high-quality used cars, and hence only the consumers in (a) will exist. Then I will only have the new car buyer and the no car buyer. Used cars of all types will have been scrapped. To prevent this from occurring, the subsidy must be such that this consumer is better off keeping the good quality cars, rather than scrapping them (more on this below).

(c) Types in $[\underline{\theta}, \theta_{nk}^{is}]$: Their lifetime utility is zero in every period.

Marginal consumers, θ_n^{is}, and θ_{nk}^{is} are defined by their respective indifference conditions, given below:

$$\begin{aligned} \frac{\theta_n^{is} - P_n + \delta S}{1-\delta} &= \frac{\theta_n^{is} - P_n + \delta(1-p)S + \delta p w_h}{1-\delta(1-p)-\delta^2 p} \\ \theta_{nk}^{is} - P_n + \delta(1-p)S + \delta p w_h &= 0 \end{aligned} \tag{3.32}$$

where θ_n^{is} is indifferent between the purchase of a new car every period and the purchase of one less often, and θ_{nk}^{is} is indifferent between the purchase of a new car and keeping it if it turns out to be a high-quality used car, and not choosing a car. The subsidy that supports the above allocation is such that the marginal consumer, θ_{nk}^{is}, must never want to keep a low-quality used car. This means $S^{is} \geq \theta_{nk}^{is} w_l$. The minimum level of this subsidy is: $S^{is} = \theta_{nk}^{is} w_l$. This equation along with the two marginal conditions determine the equilibrium. I use these equations to contrast the subsidy level required to maintain this equilibrium relative to that in the observable case, and also indicate how this subsidy affects the welfare of the different types of consumers.

3.3.4 Case 2: Subsidy with an Active Resale Market

In this case the subsidy is such that the behavior of the used car suppliers is similar to the case without the subsidy. The used car buyers, however, behave differently. All used car buyers form expectations regarding the probability that a traded used car will be of high-quality. In equilibrium this is equal to the proportion of high quality cars traded in the second-hand market. If the used car that these consumers purchase turns out to be of high-quality, they keep it, but if it turns out to be of low-quality, they scrap it. Thus, all low-quality used cars are scrapped and $Q_E^{isr} = 0$.

In equilibrium, types in $[\underline{\theta}, \theta_u^{isr}]$ do not purchase a car, types in $[\theta_u^{isr}, \theta_{nk}^{isr}]$ purchase a used car, keep it if it turns out to be of high-quality, but scrap it if it is of low-quality, types in $[\theta_{nk}^{isr}, \theta_n^{isr}]$ purchase a new car, keep the used car if it is of good quality, but sell it if it is of poor quality, and finally types in $[\theta_n^{isr}, \overline{\theta}]$ purchase a new car and resell the used car, regardless of quality. The behavior of these four types of consumer is described as follows:

(a) Types in $[\theta_n^{isr}, \overline{\theta}]$: Their lifetime utility is given as follows:

$$V_n^{isr} = \frac{\theta - P_n + \delta P_u^{isr}}{1 - \delta} \tag{3.33}$$

where P_u^{isr} is the used car price.

(b) Types in $[\theta_{nk}^{isr}, \theta_n^{isr}]$: Their lifetime utility is:

$$\begin{aligned} V_{nk}^{isr} &= \theta - P_n + \delta(1-p)[P_u^{isr} + V_{nk}^{isr}] + \delta p[\theta w_h + \delta V_{nk}^{isr}] \\ \Rightarrow V_{nk}^{isr} &= \frac{\theta(1 + \delta p w_h) + \delta(1-p)P_u^{isr} - P_n}{1 - \delta(1-p) - \delta^2 p} \end{aligned} \tag{3.34}$$

(c) Types in $[\theta_u^{isr}, \theta_{nk}^{isr}]$: If the quality of the used car they purchase is of high quality, then they continue to drive it. On the other hand, if it turns out to be of low quality, then they scrap it. Let w_u^{isr} be the consumer's belief that his or her purchased used car is of high quality. If the quality of the car that the used car buyer purchases is lower than expected, then he or she scraps it. Their lifetime utility is below:

$$V_u^{isr} = \frac{(1 - w_u^{isr})S^{isr} + w_u^{isr}\theta w_h - P_u^{isr}}{1-\delta} \tag{3.35}$$

In equilibrium w_u^{isr} is equal to the proportion of high-quality used cars being traded in the market. The no car buyers get a lifetime utility equal to zero.

On the boundary between consumers who purchase a new car every period and those who keep their used car of good quality is a marginal consumer with preference θ_n^{isr}, which is defined by his or her indifference between the two decisions. Let the marginal consumer between those who keep their high quality used cars and purchase used cars be denoted by θ_{nk}^{isr}. Lastly, let the marginal consumer indifferent between purchasing a used car and the no car option be denoted by θ_u^{isr}. The three indifference equations are given below:

$$\begin{aligned}
\frac{\theta_n^{isr} - P_n + \delta P_u^{isr}}{1-\delta} &= \frac{\theta_n^{isr}(1+\delta p w_h) + \delta(1-p)P_u^{isr} - P_n}{1-\delta(1-p)-\delta^2 p} \\
\frac{\theta_{nk}^{isr}(1+\delta p w_h) + \delta(1-p)P_u^{isr} - P_n}{1-\delta(1-p)-\delta^2 p} &= \frac{(1-w_u^{isr})S^{isr} + w_u^{isr}\theta_{nk}^{isr} w_h - P_u^{isr}}{1-\delta} \\
\frac{(1-w_u^{isr})S^{isr} + w_u^{isr}\theta_u^{isr} w_h - P_u^{isr}}{1-\delta} &= 0 \qquad (3.36)
\end{aligned}$$

The price of used cars is determined by the market clearing condition where the supply of used cars equals the demand for it.

$$F(\overline{\theta}) - F(\theta_n^{isr}) + (1-p)[F(\theta_{nk}^{isr}) - F(\theta_u^{isr})] = F(\theta_{nk}^{isr}) - F(\theta_u^{isr}) \tag{3.37}$$

I assume that the expectations of used car buyers is correct and is:

$$w_u^{sr} = \frac{p(F(\overline{\theta}) - F(\theta_n^{sr}))}{F(\overline{\theta}) - F(\theta_n^{sr}) + (1-p)[F(\theta_n^{sr}) - F(\theta_{nk}^{sr})]} \tag{3.38}$$

In the presence of information asymmetry even the highest type amongst the used car buyers can purchase a car that turns out to be of low quality. To prevent them from keeping it, the subsidy must be such that $S^{isr} \geq \theta_{nk}^{isr} w_l$, out of which the minimum level is selected. The equilibrium solution is obtained from the equations 3.36, 3.37, 3.38 and the equation for the minimum subsidy level. I use the system of equations here to compute the equilibrium allocations, compare the subsidy level obtained here to that in the observable case, and finally discuss the welfare effects of such a subsidy. I also compare the welfare results obtained here to that obtained with a subsidy that shuts down the used car market to indicate which is a more preferred outcome.

3.3.5 Optimal subsidy rate with unobservable quality

Let θ be distributed uniformly between [0,1]. Let the marginal types be: θ_u^*, θ_{uk}^*, θ_{nk}^*, θ_n^*, where types in $[0, \theta_u^*]$ purchase no car, types in $[\theta_u^*, \theta_{uk}^*]$ purchase a used car, keeps it if it is of good quality, but scraps it if it is of bad quality, types in $[\theta_{uk}^*, \theta_{nk}^*]$ buy used car, keep it regardless of quality, types in $[\theta_{nk}^*, \theta_n^*]$ purchase new cars, keep the used car if of good quality and resell if of poor quality, and finally types in $[\theta_n^*, \overline{\theta}]$ purchase new cars every period and resell the used cars in the second hand market.

The endogenous variables are: (θ_u^*, θ_{uk}^*, θ_{nk}^*, θ_n^*, w_u^*, P_u^*), where w_u^* is the expectation of the used car buyer of the average quality of the traded used car, and P_u^* is the used car price. The exogenous variable is S, whose optimal rate I want to solve for from the welfare equation.

Equations to solve for the endogenous variables in terms of S:

$$\begin{aligned}
\theta_n^* - P_n + \delta P_u^* &= \frac{\theta_n^*(1+\delta p w_h) + \delta(1-p)P_u^* - P_n}{1+\delta p} \\
-P_u^* + \theta_{nk}^*(w_u(w_h - w_l) + w_l) &= \frac{\theta_{nk}^*(1+\delta p w_h) + \delta(1-p)P_u^* - P_n}{1+\delta p} \\
\theta_{uk}^* w_l &= S \\
-P_u^* + (1-w_u)S + w_u^*\theta_u^* w_h &= 0 \\
1 - \theta_n^* + (\theta_n^* - \theta_{nk}^*)(1-p/2) &= \theta_{nk}^* - \theta_u^*
\end{aligned}$$

$$w_u^* = \frac{p(1-\theta_n^*)}{1-\theta_n^* + (\theta_n^* - \theta_{nk}^*)(1-p/2)} \tag{3.39}$$

The reduced form solution is given in Appendix F. As in the case of observable car quality, I substitute the reduced form solutions from above for the endogenous variables into the welfare function given as follows:

$$\begin{aligned}
W(S) &= \int_{\theta_n^*(S)}^{1} V_n(\theta,S)d\theta + \int_{\theta_{nk}^*(S)}^{\theta_n^*(S)} V_{nk}(\theta,S)d\theta + \int_{\theta_{uk}^*(S)}^{\theta_{nk}^*(S)} V_{uk}(\theta,S)d\theta \\
&+ \int_{\theta_u^*(S)}^{\theta_{uk}^*(S)} V_u(\theta,S)d\theta + \int_0^{\theta_u^*(S)} V_0(\theta)d\theta - \frac{S}{1-\delta}d\theta \\
&- \frac{\mu Q_E(\alpha(1-p)(\theta_{nk}^*(S) - \theta_{uk}^*(S)) + \beta p(\theta_n^*(S) - \theta_u^*(S)))}{1-\delta}
\end{aligned} \tag{3.40}$$

where $V_n(\theta)$ is the value function for new car buyers, $V_{nk}(\theta)$ is the value function for new car buyers who keep the good quality cars, $V_{uk}(\theta)$ is the value function for the types who are used car buyers that keep it regardless of quality, $V_u(\theta)$ is the value function of the used car buyer who are used car buyers, keep w_h cars and scrap w_l cars, and finally $V_0(\theta)$ is the value function for the no car owner. All endogenous variables are functions of the subsidy rate. To solve for the optimal subsidy rate, I differentiate the above function and set it equal to zero. An example is computed in section 3.4.

3.4 Numerical Section

In this section I numerically analyze each of the equilibria characterized above under the assumption that θ is uniformly distributed between 0 and 1. In particular, I focus on how the effective scrappage subsidy affects the decisions of individuals in the primary and secondary markets with and without information asymmetry. I further analyze how the policy affects the welfare of each type of consumer when quality is observable and compare the results to when quality is unobservable. The results below are presented for constant values of the following exogenous parameters: $\delta = 0.8$, $w_h = 0.5$, $P_n = 0.7$, $p = 0.6$, $\alpha = 0.2$, $\beta = 0.8$ and $\mu = 0.4$. Finally, I change these values to test the robustness of my results.

When quality is observable, the second-hand market perfectly matches cars to the "right" owners through the self-selection mechanism. This means that consumers choose used and new cars based on their respective valuations.

The consumers most sensitive to quality purchase new cars, while those that are least sensitive to quality choose low-quality used cars. In this case, the government can subsidize scrappage of the low-quality used cars by adequately compensating the highest type that owns such a car. In the presence of such a subsidy, only high-quality used cars are traded in the secondary market, while the low-quality ones are scrapped. However, this policy does not get rid of all the high-emissions cars as in my example 20 percent of high-quality cars turn out to be highly polluting.

Table 3.1 illustrates how effective the subsidy will be in reducing pollution when car quality is observable, but emissions are not.[5] Under these conditions the government has some information on the allocations of used cars of different quality. It uses this information to attract some of the polluting cars by conditioning the subsidy on car quality. The subsidy is set such that all low-quality used cars are scrapped. This still leaves the polluting high-quality vehicles on the road. The subsidy acts as a price floor in the low-quality used car market, thereby raising the resale price of a new car if it turns out to be of low-quality. Some prior owners of low-quality used cars now switch to buying high-quality used cars. Thus, in the presence of the subsidy the marginal high-quality used car buyer falls from 0.494 to 0.473 (columns 2 and 3). The greater demand for high-quality used cars raises its price from 0.234

[5]Emissions is never observable to the government. The paper examines whether the government can still run an effective scrappage program aimed at reducing pollution in the absence of information. It can be effective in reducing pollution significantly if emissions and quality are very negatively correlated.

to 0.236. A new car now becomes more attractive as its salvage value rises due to both the scrappage subsidy and the higher price for high-quality used cars. Thus, more consumers participate in the primary market as the marginal new car buyer falls from 0.683 to 0.670. Moreover, the effective subsidy in this case is at its minimum level at 0.047.

The optimal subsidy is calculated at the point where marginal environmental benefits from scrappage equal the marginal costs in terms of utility lost from substituting to cars of higher quality or to the no-car option. When quality is observable, the optimal subsidy rate is $S_o^* = 0.023 = P_l^*$. This is below the subsidy rate that the government sets to induce all low-quality used cars to scrap. I examine below how this optimal value of the subsidy changes with changes in μ, α and β.

When quality and emissions are unobservable, on the other hand, the seller of a car has more information about its quality than the prospective buyer, and this adversely affects the average quality of cars traded in the second-hand market. In the presence of such information asymmetry, a higher valuation consumer relative to the case when only car quality is observable can get a low-quality used car. The government wants to scrap the most polluting cars. Since it cannot observe emissions it offers a subsidy to adequately compensate the highest type amongst used car buyers in this case and gets a mix of low-quality and high-quality cars. I compare the subsidy levels and the level of aggregate emissions that result in the two equilibria possible with information asymmetry to that in the observable case.[6] More on each of these equilibria below.

Table 3.2 illustrates the effects of the subsidy that maintains an active resale market in the presence of information asymmetry. The government achieves effective scrappage with a subsidy less than the used car price (column 3). All used car sellers re-sell their low-quality cars in the secondary market. The used car price ($P_u^{isr} = 0.118$) lies below the value that the lowest type amongst the used car buyers gets from a high-quality car ($\theta_u^{isr} w_h = 0.165$), but it lies above the value that the highest type amongst the used car buyers gets from a low-quality used car ($\theta_{nk}^{isr} w_l = 0.053$). Thus, a typical used car buyer would like to only buy and keep a high-quality used car. However, with information asymmetry these types cannot separate a good quality car from a bad one. With a subsidy in such a market, types in $[\theta_u^{isr}, \theta_{nk}^{isr}]$ keep the high-quality car since their benefit from it is greater than the used car price, and hence the subsidy. However, they scrap the low-quality used car as their benefit from it is below the used car price and hence the subsidy.

Table 3.2 also shows what replacement options the prior low-quality used car buyers choose in the presence of the subsidy. Some consumers who previously chose the no-car option, now switch to purchasing a used car that they scrap if it is of low quality, and keep if it is of high quality. In Table 3.2 this is seen from the fact that the lowest type to purchase a used car falls from

[6]The two equilibria described here are not multiple equilibria as one of them ceases to exist for some parameter values.

0.376 to 0.331. This higher demand raises the used car price from 0.116 to 0.118. This in turn causes some new car buyers who were previously keeping the high-quality used car to re-sell it and participate in the primary market at the end of every period. Thus, the marginal buyer to purchase a new car every period falls from 0.983 to 0.976. This greater participation in the secondary market by the higher type of car owners raises the average quality of the traded car from 0.055 to 0.341, thereby inducing some prior used car buyers to switch to a new car and to keep the high-quality realizations. The marginal consumer of this type falls from 0.562 to 0.533.

Comparing results in the observable case to that in the unobservable case without the subsidy (column 2 in Tables 3.1 and 3.2), I find that the quantity of emissions generated is greater with information asymmetry. This is an expected result but important to interpret from an environmental perspective. When quality is unobservable, used car buyers expect the average quality of the traded car to be less than the average quality of all used cars. Hence, the high-quality used car is priced according to the used car buyers' expectations, thereby reducing its price and causing a positive measure of new car buyers to keep their high-quality used cars. This implies that low-quality used cars constitute a greater proportion of trade in the second-hand

I also examine how information asymmetry affects the minimum level of the effective subsidy required to achieve the goal of attracting the poorest quality of cars in the hope of reducing the proportion of the most polluting cars on the road. The subsidy required to scrap all the low-quality cars when quality and emissions are unobservable is higher ($S^{isr} = 0.053$) than that under the case when quality is observable, but emissions is not ($S^{os} = 0.047$). This is because when quality is observable, but emissions is not, the subsidy must ensure that the highest type amongst the consumers who choose the no-car option, θ_h^{os}, must prefer this decision to purchasing a low-quality used car. However, under the unobservable case the subsidy must ensure that the highest type amongst the used car buyers, θ_{nk}^{isr}, prefers to scrap a low-quality car than to use it. As seen from column 3 in Tables 3.1 and 3.2, the highest type who does not purchase a car under the observable case ($\theta_h^{os} = 0.473$) is lower than the highest type who purchases a used car in the unobservable case ($\theta_{nk}^{isr} = 0.533$). Thus, the subsidy required for effective scrappage is higher in the latter case than in the former.

The equilibrium with a subsidy that maintains an active resale market exists only for some parameter spaces. In Section 3.4.2 below I further characterize this parameter space. When this equilibrium does not exist, then the government can implement the subsidy at a level that shuts down the resale market. In Tables 3.3 and 3.4 I compute the equilibria for the observable and unobservable cases respectively, for values of the parameters under which a resale market cannot exist with the scrappage subsidy. Results in Table 3.3 follow the same intuition as those in Table 3.1. But I present it again in order to compare the results to the unobservable case without the secondary market. In the presence of a subsidy that closes the resale market, the owners who choose a new car at the end of a period prefer to scrap their used car regardless of quality, rather than re-sell it. Thus, the government subsidizes scrappage of the high-quality cars along with the low-quality cars.

Comparing columns 2 and 3 in Table 3.4, I see that some prior used car buyers switch to purchasing a new car and keeping the high-quality used car. The marginal consumer who keeps w_h falls from 0.588 to 0.530. This switch is greater in this case than that under the unobservable case with the active resale market as the new car is the relevant substitute for prior used car buyers. The subsidy raises the salvage value of the new car and makes it more attractive to purchase a new car now than before, thereby raising its demand. The marginal consumer purchasing a new car every period falls from 0.991 to 0.923. Moreover, the effective subsidy in this case ($S^{is} = 0.133$)is higher than the one in Table 3.2 ($S^{isr} = 0.053$).

When quality is unobservable, the optimal subsidy rate is $S_o^* = 0.053$, which is also below the level set for scrappage of all low-quality used cars, but above its level when quality is observable. I examine the sensitivity of this result with respect to changes in μ, α, and β.

3.4.1 Welfare Implications

Here I provide some intuition regarding how the scrappage program affects the welfare of each type of consumer in the observable and unobservable cases. I first look at how each type of consumer fares in the presence of a subsidy relative to without it when car quality is observable (Table 3.1). As seen in Section 3.2.2, three types of consumers exist here: those who choose not to buy a car, those who purchase a high-quality used car, and those who purchase a new car at the end of every period.

(1) Types in $[\underline{\theta}, \theta_h^{os}]$: These are the consumers who choose the no-car option in the presence of the subsidy. Some amongst these types who were choosing this option even in the absence of a subsidy become better off under the subsidy due to the environmental gain. However, some prior low-quality used car buyers now switch to not purchasing a car. They lose the benefit of driving a car, but can become better off than before if the environmental gain outweighs their loss. Thus, the net effect on this type is ambiguous.

(2) Types in $[\theta_h^{os}, \theta_n^{os}]$: These are the buyers of high-quality used cars. The welfare effects on these buyers are similar to that of the no-car buyers. Those who choose the high-quality car with and without a subsidy are better off, but those who switch from a low-quality to a high-quality used car experience a lower surplus from driving. In this equilibrium the latter types are better off driving a high-quality used car to not driving one at all. However, if a high-quality used car is their first best choice, then they would have been choosing it irrespective of the subsidy. These types might still become become better off if the gain from improved air quality outweighs the loss in surplus.

(3) Types in $[\theta_n^{os}, \overline{\theta}]$: These buyers purchase a new car at the end of every period and the policy makes all types in this category unambiguously

better off. The subsidy makes those who were always choosing this option better off due to a higher resale price for every quality realization of their used car. This higher benefit from driving reinforces the gain from improved air quality. Those who switch to this option under the subsidy from a high-quality used car also benefit from the scrappage policy. This is because the benefit from driving a good-quality used car for these latter types is reduced due to the higher price. Moreover, a new car is more attractive under the subsidy because it fetches a higher price when it turns into a good-quality used car as well as when it turns out to be a poor-quality used car.

Thus, while the highest valuation consumers are the winners of the scrappage program, the used car buyers and those who choose the no-car option could worse off. Consequently when quality is observable, aggregate welfare with a subsidy when quality is observable might be lower than that without the subsidy.

Next, I examine the welfare effects of the subsidy that maintains a resale market in the unobservable case to that of the case without a subsidy (Table 3.2). In this case, I have four types of consumers: those who always purchase a new car at the end of the first period, those who purchase a new car, and keep the high-quality used car, used car buyers, and those who do not purchase a car.

(1) Types in $[\theta_n^{isr}, \overline{\theta}]$: These consumers purchase a new car at the end of a

period. Prior new car buyers that continue with the same decision in the presence of the subsidy become better off as they get a higher price for every type of used car, while the new car price is held constant. Those who switch to purchasing a new car at the end of every period from purchasing a new car, but keeping their high-quality used car, are also better off. The reason why these types were choosing not to purchase a new car at the end of every period is because the resale price for the good quality used car was too low. But the used car price rises in the presence of the subsidy. Thus, the types who switch over get a higher surplus from driving a new car and this gain in surplus reinforces their environmental benefit. Thus, all new car buyers are made unambiguously better off by the subsidy.

(2) Types in $[\theta_{nk}^{isr}, \theta_{n}^{isr}]$: These consumers choose a new car, keep the high-quality used car, and resell the low-quality car. All consumers who choose this option with and without the subsidy are better off because they get a greater compensation for their low-quality used car due to the scrappage subsidy than they were getting from the used car price before. Moreover, prior used car buyers now switch to being a type in $[\theta_{nk}^{isr}, \theta_{n}^{isr}]$ because the new car is more attractive due to the higher price of the used car. Their valuations from driving a car are not high enough for them to drive a new car every period. Hence those who were previously purchasing a used car now replace it with a new car in the first period and with a high-quality used car in the second. Thus all types in this

category are unambiguously better off by the subsidy.

(3) Types in $[\theta_u^{isr}, \theta_{nk}^{isr}]$: These are the used car buyers. The prior used car buyers who continue to choose this option are worse off due to the higher price they now have to pay for their used car. However, the subsidy more than compensates them for the rise in the price of the used car (See Table 3.2). Moreover, some consumers switch over from the no-car option to the used car option since it makes them better off, otherwise they would have continued to not purchase a car.

(4) Types in $[\underline{\theta}, \theta_u^{isr}]$: These are the no-car buyers. All of these buyers are made better off by the subsidy due to the environmental gain.

Thus, the subsidy that maintains a resale market unambiguously makes all types of consumers better off than they were without it when quality is unobservable. The subsidy can increase aggregate welfare if the cost of the subsidy does not outweigh the higher benefit to all consumers.

Lastly, I compare how the subsidy affects the welfare of consumers when it can only be implemented without a resale market (Table 3.4). Here I have three types of consumers: new car buyers, those who purchase a new car, keep it after a period if it is of high-quality, and scrap it after the first period if it turns out to be of low-quality.

(1) Types in $[\theta_n^{is}, \overline{\theta}]$: These are the new car buyers. Those new car buyers who were choosing this option with and without a subsidy are unambiguously better off as the subsidy is giving them a better resale price

for their used car. Those who switch to this option are also made unambiguously better off because this is the first best choice for these types. The only reason they were not choosing to do so is because the used car price was too low for them to re-sell the high-quality used car. The subsidy now offers them a greater return for their used car and causes some of them to switch to purchasing a new car at the end of every period.

(2) Types in $[\theta_{nk}^{is}, \theta_n^{is}]$: These consumers purchase a new car, keep the used car if it is of high quality and scrap it if it is of low quality. Those amongst this type that continue with the same decision before and after the subsidy are unambiguously better off. This is because while consuming the same quality car, they now receive a higher price for the low-quality used car, and also derive environmental benefits due to the policy. However, the welfare effect of the subsidy on those amongst this type who switch over from purchasing a used car is ambiguous. Now even though these types enjoy the higher services from a new car in the first period and a high-quality used car in the second, their valuation for quality might not be high enough to adequately compensate them for the higher new car price. So choosing this option for these types might be better than not purchasing a car, but it might make them worse off than they were in the absence of the subsidy. Thus, those who switch over to being in this category enjoy a lower surplus from driving. However, they could still be better off with the subsidy if the benefits from higher air quality compensate them for this reduced surplus.

(c) Types in $[\underline{\theta}, \theta_{nk}^{is}]$: These are the no car buyers. Amongst the no-car buyers, those who choose this with and without the subsidy are made better off due to the benefit from cleaner air. However, some prior used car buyers now switch to the no-car option as the next best option of purchasing a new car is too expensive in relation to their valuation for quality. Hence, they might be made worse off if the environmental gain does not outweigh their utility loss from driving a car.

The discussion above suggests that the subsidy that maintains the resale market makes all types of consumers unambiguously better off than they were in the absence of it, when quality is unobservable. Moreover, it achieves scrappage at a lower rate than the subsidy that shuts down the secondary market. Hence if the cost of the subsidy to society does not outweigh the utility gain to all types of consumers, then it is a Pareto-improvement to subsidize scrappage of low-quality cars (most of which are polluting) while maintaining the resale market.

3.4.2 Sensitivity Results

In Table 3.5, I characterize the parameter space within which an equilibrium with a resale market exists along with its sensitivity to changes in the parameter values. I use the following parameters as the benchmark for comparison: $\delta = 0.8$, $w_h = 0.5$, $P_n = 0.7$, $p = 0.6$, $w_l = 0.1$, $\alpha = 0.8$, $\beta = 0.2$, and $\mu = 0.4$. First, I change the value of the probability of a used car being of high-quality (p). The equilibrium with an active resale market exists for all values of p higher than the benchmark value, but it ceases to exist if p falls below 0.436, given values of all other parameters. Then the equilibrium switches to the one without a resale market. If p rises above 0.6, the subsidy under the resale market rises, while if it falls below 0.6 and above 0.436, then the subsidy falls. When p rises, the average quality of the traded car rises due to higher expectations. This raises the used car price, causing more consumers who previously kept w_h to resell their cars. Thus, t_{nk} rises and hence a greater compensation is required to induce scrappage. The opposite occurs when p falls below 0.6. Under the equilibrium without resale, the sensitivity of the subsidy moves in the opposite direction. As p falls, the subsidy levels rise. This is because the new car is less likely to be a high-quality car, and thereby reduces its attractiveness. Hence, the marginal consumer who purchases a new car and keeps w_h used car rises relative to the benchmark case, and hence the subsidy rises.

Next I change the value of w_h. The equilibrium with resale exists for all lower values of w_h, but ceases to exist if it rises above 0.73. The subsidy under resale falls with higher values of w_h, but rises when w_h falls. When w_h rises, the new car becomes more attractive, and t_n falls. Also, more consumers are willing to keep the w_h used cars, causing t_{nk} and hence the subsidy to fall. The subsidy in the absence of a resale also falls when w_h rises. The opposite occurs when w_h falls, causing the subsidy to rise. Next, I test the sensitivity of the equilibria for different values of w_l. The equilibrium with resale exists for values of w_l below 0.1, and the subsidy falls with lower values of w_l. If this parameter is above 0.25, then we get the equilibrium without a resale market. The subsidy level here rises with higher values of w_l. When w_l rises, the logic is the same as when w_h falls, and vice-versa.

Finally, I observe how the optimal subsidy rate changes when quality is observable and unobservable. The results are presented in Table 3.5. When the probability that a low-quality car is polluting relative to a high-quality used car is held constant, along with other parameters and μ is increased (reduced), the optimal subsidy rises (falls) in both cases as the damages from pollution rises (falls). A similar effect is observed when α is raised (reduced) holding all else constant. Both of these parameters affect the damages from pollution generated by the used cars, causing the subsidy to be changed accordingly.

3.5 Conclusion

I have shown that information asymmetry has non-trivial effects on the scrappage subsidy and the welfare implications of the resulting replacement choices. One key result is that in the presence of adverse selection in the second-hand automobile market, a subsidy that maintains a resale market unambiguously makes all types of consumers better off. However, if this option of implementing the subsidy does not exist, then it might be better not to do anything rather than have a scrappage program that shuts down the second-hand market. Moreover, the subsidy with a resale market achieves the government's goal at a lower cost relative to the subsidy that shuts down the resale market. Finally, the optimal subsidy for scrappage is lower than the subsidy currently used to scrap all low-quality used cars. A relevant extension to this work would be to to compare the welfare effects of the scrappage subsidy to other forms of environmental policy, such as taxes on new and used vehicles.

Table 3.1: Allocation of cars, Subsidy rate and Emissions when Car Quality is observable, and with a low-quality used car significantly inferior to a high-quality used car ($w_l = 0.1$)

Variables (1)	No Subsidy (2)	With Subsidy (3)
θ_l^o (1)	0.367	-
θ_h^o (2)	0.494	0.473
θ_n^o (3)	0.683	0.670
P_h (4)	0.234	0.236
P_l (5)	0.037	-
Subsidy (6)	0	0.047
Traded w_h cars	0.6	0.6
Emissions (7)	0.063	0.0394

The variables names in Column 1 are as follows: θ_l^o stands for marginal low-quality used car buyer, θ_h^o stands for marginal high-quality used car buyer, $theta_n^o$ is the marginal new car buyer, P_h is the price of high-quality used cars, and P_l is the price of low-quality used cars. Exact values of other parameters are: $\delta = 0.8$, $w_h = 0.5$, $P_n = 0.7$, $p = 0.6$, $\alpha = 0.2$, $\beta = 0.8$ and $\mu = 0.4$. The emissions function is: $Q_E = \beta q_l + \alpha q_h$, where q_h is quantity of high-quality used cars, and q_l is the quantity of low-quality used cars. All numbers in the table are expressed as fractions of the total population of individuals.

Table 3.2: Allocation of cars, Subsidy rate and Emissions when Car Quality is Unobservable, and with a low-quality used car significantly inferior to a high-quality used car ($w_l = 0.1$) in the Presence of a Resale Market

Variables (1)	No Subsidy (2)	Subsidy (3)
Marginal used car buyer (1)	0.376	0.331
Marginal new car buyer, keeps w_h (2)	0.562	0.533
Marginal new car buyer (3)	0.983	0.976
w_u (4)	0.254	–
Traded w_h cars (5)	0.055	0.341
P_u (6)	0.116	0.118
Subsidy (7)	0	0.053
Emissions (8)	0.132	0.077

The variables names in Column 1 are as follows: w_u is the expectation of a high-quality used car, and P_u is the price of used cars. Exact values of other parameters are: $\delta = 0.8$, $w_h = 0.5$, $P_n = 0.7$, $p = 0.6$, $\alpha = 0.2$, $\beta = 0.8$ and $\mu = 0.4$. The emissions function is: $Q_E = \beta q_l + \alpha q_h$, where q_h is quantity of high-quality used cars, and q_l is the quantity of low-quality used cars. All numbers in the table are expressed as fractions of the total population of individuals.

Table 3.3: Allocation of cars, Subsidy rate and Emissions when Car Quality is Observable, and with a low-quality used car not so inferior to a high-quality used car ($w_l = 0.25$)

Variables (1)	No Subsidy (2)	Subsidy (3)
Marginal low-quality buyer (1)	0.378	-
Marginal high-quality buyer (2)	0.502	0.453
Marginal new car buyer (3)	0.689	0.658
P_h (4)	0.220	0.226
P_l (5)	0.094	-
Subsidy (6)	0	0.113
Emissions (7)	0.2086	0.041

The variables names in Column 1 are as follows: P_h is the price of high-quality used cars, and P_l is the price of low-quality used cars. Exact values of other parameters are: $\delta = 0.8$, $w_h = 0.5$, $P_n = 0.7$, $p = 0.6$, $\alpha = 0.2$, $\beta = 0.8$ and $\mu = 0.4$. The emissions function is: $Q_E = \beta q_l + \alpha q_h$, where q_h is quantity of high-quality used cars, and q_l is the quantity of low-quality used cars. All numbers in the table are expressed as fractions of the total population of individuals.

Table 3.4: Allocation of cars, Subsidy rate and Emissions when Car Quality is Unobservable, with a low-quality used car not so inferior to a high-quality used car ($w_l = 0.25$) and without Resale Market

Variables (1)	No Subsidy (2)	Subsidy (3)
Marginal used car buyer (1)	0.417	–
Marginal new car buyer, keeps w_h (2)	0.588	0.530
Marginal new car buyer every period (3)	0.991	0.923
w_u (4)	0.270	–
Proportion of Traded w_h cars (5)	0.032	–
P_u (6)	0.114	–
Subsidy (7)	0	0.133
Emissions (8)	0.062	0.047

The variables names in Column 1 are as follows: w_u is the expectation of a high-quality used car, and P_u is the price of used cars. Exact values of other parameters are: $\delta = 0.8$, $w_h = 0.5$, $P_n = 0.7$, $p = 0.6$, $\alpha = 0.2$, $\beta = 0.8$ and $\mu = 0.4$. The emissions function is: $Q_E = \beta q_l + \alpha q_h$, where q_h is quantity of high-quality used cars, and q_l is the quantity of low-quality used cars. All numbers in the table are expressed as fractions of the total population of individuals.

Table 3.5: Sensitivity Results to illustrate changes in the Subsidy Rate when Car Quality is Unobservable, Base Parameter Values: $w_l = 0.1$, $w_h = 0.5$, $P_n = 0.7$, $\delta = 0.8$, $p = 0.6$

PARAM.		RESALE						NO RESALE		
		θ_u	θ_{nk}	t_n	q_h	P_u	S	θ_{nk}	t_n	S
p	0.6	0.33	0.53	0.976	0.34	0.118	.053	-	-	-
p	0.7	0.36	0.56	0.906	0.536	0.137	.056	-	-	-
p	0.5	0.34	0.54	1.065	0.203	0.093	.054	-	-	-
p	0.4	-		-	-	-	-	.579	1.191	.057
w_h	0.4	0.37	0.55	0.996	0.021	0.057	.055	-	-	-
w_h	0.6	0.30	0.52	0.942	0.18	0.595	.052	-	-	-
w_h	0.8	-		-	-	-	-	.616	2.945	.062
w_h	0.9	-		-	-	-	-	.478	6.139	.048
w_l	0.3	-		-	-	-	-	.557	0.798	.167
w_l	.05	0.34	0.54	0.977	0.431	0.117	.027	-	-	-
P_n	0.8	0.44	0.63	0.921	0.621	0.188	.063	-	-	-
P_n	0.5	0.12	0.44	0.824	0.322	0.049	.044	-	-	-
P_n	0.4	-		-	-	-	-	.36	0.671	.036
δ	0.7	0.35	0.55	0.968	0.372	.127	.055	-	-	-
δ	0.9	0.31	0.51	0.983	0.312	.11	.051	-	-	-

The parameters being changed are: the probability of a car being of high-quality (p), the quality level of a high-quality used car (w_h), the quality level of a low-quality used car (w_l), the new car price (P_n), and the discount rate (δ). The column headings in the second row are as follows: θ_u is the marginal used car buyer, θ_{nk} is the marginal new car buyer who keeps w_h, t_n is the marginal new car buyer, q_h is the proportion of high-quality used cars being driven, P_u is the used car price, and S is the scrappage subsidy. Either one of two equilibria exist: one with a resale market and the other without. The first row of numbers shows the results for the case where all the parameters are at their base values as given in the heading. All numbers in the following rows are to be compared to this first row. When one parameter is being changed, all others are held at their base values. An example of how to read the table: if p rises from its base value to 0.7, then the subsidy rate rises to 0.056.

Table 3.6: Sensitivity Results to illustrate changes in the Optimal Subsidy Rate

PARAMETERS		Observable Quality	Unobservable Quality
β	μ	S_o^*	S^*
0.8	0.5	0.047	0.076
0.8	0.6	0.082	0.093
0.8	0.3	0.021	0.048
0.7	0.4	0.033	0.067
0.6	0.4	0.045	0.058
0.9	0.4	0.018	0.041

Parameters being changed are: β which is the probability of a low-quality used car being polluting, and μ which is the marginal damage from emissions. The last two column headings are: S_o^* stands for the optimal subsidy rate when car quality is observable, and S^* stands for the optimal subsidy rate when car quality is unobservable. Base values of the parameters are: $\delta = 0.8$, $w_h = 0.5$, $w_l = 0.1$, $P_n = 0.7$, $p = 0.6$, $\alpha = 0.2$, $\beta = 0.8$ and $\mu = 0.4$. The first three rows of results show how the optimal subsidies change with μ, and the last three rows show how the subsidies change with higher β.

Appendices

Appendix A

Impact of Emissions restriction on utility (Equation 1.19)

First, totally differentiating utility in 3.1 (holding G fixed)[1]:

$$dU = U_X dX_C + U_Y dY_C + U_{TA} dT_A + U_{TZ} dT_Z - U_H dL + U_Q Q_Z N dZ_T \quad \text{(A.1)}$$

To balance the government's budget, any environmental policy that reduces labor supply must also specify how the lost labor tax revenue will be recovered. Substituting the first order conditions into A.1 yields:

$$dU = \lambda P_X^D dX_C + \lambda dY_C + \lambda \frac{(1 - s_A)}{\frac{\partial T_A}{\partial A}} dT_A + \lambda \frac{(P_Z^D + t_{ZT})}{\frac{\partial T_Z}{\partial Z_T}} dT_Z - \lambda(1 - t_L) dL + U_Q Q_Z N dZ_T$$

Totally differentiate resource constraints in 1.15, 1.16, 1.17, and 1.13, as well as the production function of Y with $dG = 0$, and substitute into A.2:

$$\begin{aligned} \frac{dU}{\lambda} &= t_L dL + \frac{(1 - s_A)}{\frac{\partial T_A}{\partial A}} dT_A + \frac{(P_Z^D + t_{ZT})}{\frac{\partial T_Z}{\partial Z_T}} dT_Z \\ &- P_Z^D dZ_T - P_X^D dX_A - dV - dA - \mu dZ_T \end{aligned} \quad \text{(A.2)}$$

where μ is defined as $-\frac{NU_Q Q_Z}{\lambda}$. Next, I need expressions for $\frac{dT_A}{\partial T_A / \partial A}$ and $\frac{dT_Z}{\partial T_Z / \partial Z_T}$ in terms of observable variables. Totally differentiate the sub-utility functions,

[1] This G is required in the model to justify the collection of taxes

T_A and T_Z in 1.6 and 1.7 and divide both sides of each equation by $\partial T_Z/\partial Z_T$ and $\partial T_Z/\partial Z_T$ respectively:

$$\frac{dT_A}{\partial T_A/\partial A} = = dA + \frac{\partial T_A/\partial X_A}{\partial T_A/\partial A}dX_A \tag{A.3}$$

$$\frac{dT_Z}{\partial T_Z/\partial Z_T} = dZ_T + \frac{\partial T_Z/\partial V}{\partial T_Z/\partial Z_T}dV \tag{A.4}$$

Assuming implicit profit maximization in T_A and T_Z, the ratio of the marginal products from the first order conditions are: $\frac{\partial T_A/\partial X_A}{\partial T_A/\partial A} = \frac{P_X^D - s_{XA}}{1-s_A}$ and $\frac{\partial T_Z/\partial V}{\partial T_Z/\partial Z_T} = \frac{1}{P_{ZT}+t_{ZT}}$. Substitute these into A.3 and A.4:

$$\frac{dT_A}{\partial T_A/\partial A} = dA + \frac{P_X^D - s_{XA}}{1 - s_A}dX_A \tag{A.5}$$

$$\frac{dT_Z}{\partial T_Z/\partial Z_T} = dZ_T + \frac{1}{P_{ZT} + t_{ZT}}dV \tag{A.6}$$

Substitute A.5 and A.6 into A.2, and convert all changes into percentages:

$$\frac{dU}{\lambda I} = \frac{t_L L}{I}\hat{L} + \frac{(t_{ZT} - \mu)Z_T}{I}\hat{Z_T} - \frac{s_{XA}X_A}{I}\hat{X_A} - \frac{s_A A}{I}\hat{A} \tag{A.7}$$

Next, totally differentiate the sub-utility functions T_A and T_Z in 1.6 and 1.7 and substitute their FOCs,

$$\hat{T_A} = \gamma_{XA}\hat{X_A} + (1 - \gamma_{XA})\hat{A} \tag{A.8}$$

$$\hat{T_Z} = \gamma_{ZT}\hat{Z_T} + (1 - \gamma_{ZT})\hat{V} \tag{A.9}$$

Totally differentiate the sub-utility function $T = T(T_A, T_Z)$, and substitute the FOC to get:

$$\hat{T} = (1 - \alpha_{TZ})\hat{T_A} + \alpha_{TZ}\hat{T_Z} \tag{A.10}$$

where $\alpha_{TZ} = \frac{P_{TZ} T_{ZT}}{P_T T}$. To derive the change in the transportation index P_T, I totally differentiate the implicit zero profit condition and then substitute A.10 to get:

$$\hat{P_T} = \alpha_{TZ} \hat{P_{TZ}} + (1 - \alpha_{TZ}) \hat{P_{TA}} \tag{A.11}$$

Totally differentiate 1.15, 1.27, substitute for dX^S and dX^E into the differentiated 1.15, convert all changes to their respective "hat" forms, and use $\hat{X^S} = \hat{L_X} = 0$ to get the following expression for $\hat{X_C}$:

$$(P_X^D X_C)\hat{X_C} = -Y^M \hat{Y^M} - (P_Z^D Z_T)\hat{Z_T} - (P_X^D X_A)\hat{X_A} \tag{A.12}$$

Similarly, totally differentiate 1.16, 1.2, substitute for dY^S into the differentiated 1.16 to get the following expression for $\hat{Y_C}$:

$$Y_C \hat{Y_C} = L_Y \hat{L_Y} + Y^M \hat{Y^M} - V\hat{V} - A\hat{A} \tag{A.13}$$

Appendix B

Impact of Emissions restrictions on change in gas tax (Equation 1.30)

The elasticities of substitution in the two transportation sectors defined in 1.23 and 1.24 are reduced to:

$$\hat{X_A} = \hat{A} = \hat{T_A} \tag{B.1}$$

$$\hat{Z_T} = \hat{V} - \sigma_{TZ}\hat{t_{ZT}} \tag{B.2}$$

I get $\hat{X_A} = \hat{A}$ because $\hat{s_{XA}} = \hat{s_A} = 0$. Substitute for $\hat{A}$ from B.1 into 1.28:

$$\hat{t_L} = -\frac{t_L}{1-t_L}\hat{L} - \frac{t_{ZT}Z_T}{(1-t_L)L}\hat{Z_T} - \frac{(P_Z^D + t_{ZT})Z_T}{(1-t_L)L}\hat{t_{ZT}} + \frac{s_{XA}X_A + s_A A}{(1-t_L)L}\hat{X_A} \tag{B.3}$$

Substitute expression for $\hat{t_L}$ from B.3 into $\hat{w} = -\hat{t_L} - \phi_{ZT}\hat{t_{ZT}}$ to get:

$$\hat{w} = \frac{t_L}{1-t_L}\hat{L} + \frac{t_{ZT}Z_T}{(1-t_L)L}\hat{Z_T} + \phi_{ZT}\frac{I^\pi}{wL}\hat{t_{ZT}} - \frac{s_A A + s_{XA}X_A}{(1-t_L)L}\hat{X_A} \tag{B.4}$$

Using the definition of σ_T, B.1, A.9 and substituting for $\hat{V}$ from B.2, I get:

$$\hat{X_A} = \hat{Z_T} + [(1-\gamma_{ZT})\sigma_{TZ} + \sigma_T\gamma_{ZT}]\hat{t_{ZT}} \tag{B.5}$$

Substitute B.5 into 1.29:

$$\begin{aligned}\hat{L} &= \frac{1}{1-t_l-\epsilon t_L}[(\epsilon(t_{ZT}\frac{Z_T}{L})\hat{Z_T} - \epsilon(s_A\frac{A}{L} + s_{XA}\frac{X_A}{L})(\hat{Z_T} + [(1-\gamma_{ZT})\sigma_{TZ} + \sigma_T\gamma_{ZT}]\hat{t_{ZT}}) \\ &+ (1-t_L)(\frac{\epsilon I^\pi}{wL} - \eta(\delta_R + \delta_Z))\phi_{ZT}\hat{t_{ZT}}]]\end{aligned} \tag{B.6}$$

I know that $\hat{C} = \hat{X_C} = \hat{Y_C}$ and substitute that into the definition for σ_J to get:

$$\hat{X_C} = \hat{T} + \sigma_J \hat{P_T} \tag{B.7}$$

Substitute A.9 and B.2 into A.10 and use the resulting expression for $\hat{T}$ with B.5 and substitute into B.7 to get:

$$\hat{X_C} = \hat{Z_T} + [(1-\gamma_{ZT})\sigma_{TZ} + \sigma_T \gamma_{ZT}]\hat{t_{ZT}} \tag{B.8}$$

Add A.12 to A.13, use $\hat{X_A} = \hat{A}$, $L\hat{L} = L_Y \hat{L_Y}$ and $\hat{X_C} = \hat{Y_C}$ and substitute for $\hat{V}$ from B.2:

$$(P_X^D X_C + Y_C)\hat{X_C} = -(P_Z^D Z_T)\hat{Z_T} - (P_X^D X_A + A)\hat{X_A} + L\hat{L} - V(\hat{Z_T} + \sigma_{TZ}\hat{t_{ZT}}) \tag{B.9}$$

Substitute for $\hat{X_C}$ from B.8, for $\hat{X_A}$ from B.5, and finally for $\hat{L}$ from B.6 into B.9 to get 1.30. The change in total labor supply is obtained by substituting 1.30 and B.5 into 1.29 to get:

$$\begin{aligned}
\hat{L} &= \frac{1}{1-t_l-\epsilon t_L}[(\epsilon(t_{ZT}\frac{Z_T}{L})\hat{Z_T} - \epsilon(s_A\frac{A}{L} + s_{XA})\frac{X_A}{L})[1 + ((1-\gamma_{ZT})\sigma_{TZ} + \sigma_T\gamma_{ZT})\frac{C_1}{C_2}]) \\
&+ (1-t_L)\phi_{ZT}\frac{C_1}{C_2}(\frac{\epsilon I^\pi}{wL} - \eta(\delta_R + \delta_Z))]\hat{Z_T} \\
&= C_3\hat{Z_T}
\end{aligned} \tag{B.10}$$

Substitute B.10, 1.36 and 1.30 into 1.28 to get:

$$\begin{aligned}
\hat{t_L} &= [-\frac{t_L}{1-t_L}C_3 - \frac{t_{ZT}Z_T}{(1-t_L)L} - \frac{(P_Z^D + t_{ZT})Z_T}{(1-t_L)L}\frac{C_1}{C_2} \\
&+ \frac{s_{XA}X_A + s_A A}{(1-t_L)L}(1 + ((1-\gamma_{ZT})\sigma_{TZ} + \sigma_T\gamma_{ZT})\frac{C_1}{C_2})]\hat{Z_T} \\
&= C_4\hat{Z_T}
\end{aligned} \tag{B.11}$$

Substitute B.11 and 1.30 into $\hat{w} = -\hat{t_L} - \hat{P}_J$:

$$\hat{w} = -(C_4 + \phi_{ZT}\frac{C_1}{C_2})\hat{Z}_T \tag{B.12}$$

Finally, substitute 1.30 into B.8 to get:

$$\hat{C} = \hat{X_C} = \hat{Y_C} = [1 + ((1-\gamma_{ZT})\sigma_{TZ} + \sigma_T\gamma_{ZT})\frac{C_1}{C_2}]\hat{Z_T} \tag{B.13}$$

$$\begin{aligned}\frac{dU}{I\lambda} &= \frac{\epsilon t_L t_{ZT}(Z_T/I)}{1-t_L-\epsilon t_L}\hat{Z}_T + \frac{(1-t_L)t_L(L/I)}{1-t_L-\epsilon t_L}\phi_{ZT}\frac{C_1}{C_2}(\frac{\epsilon I^\pi}{wL} - \eta(\delta_R+\delta_Z))\hat{Z_T} \\ &- (\frac{s_{XA}X_A + s_A A}{I})(\frac{1-t_L}{1-t_L-\epsilon t_L})\hat{X_A} + (t_{ZT}-\mu)(Z_T/I)\hat{Z_T}\end{aligned} \tag{B.14}$$

If the initial value of the gas tax is zero or anywhere below the Pigouvian tax, then the fourth term is an unambiguous gain from pollution abatement. Pre-existing subsidies to ethanol and AFV, a rise in ethanol consumption and the number of AFVs reduces welfare (third term). The greater is the value of pre-existing subsidies to the overall size of the economy, the larger is the magnitude of this impact. The first term represents the direct cost of restricting emissions and has a negative effect on welfare. The second term encompasses the impact of pollution restriction on compensated labor supply, which was positive from earlier discussions and thus, has a positive effect on welfare. However, the net effect on welfare then depends on specific values of the parameters as well as on how high is the initial value of the gas tax. Note that in the absence of pre-existing taxes on gasoline and subsidies to AFVs and AF, an emissions restriction achieved through a higher gas tax results in a double dividend.

Appendix C

Impact of emissions restriction, given $\hat{s_A}$ on $s_{\hat{X}A}$ (Equation 1.44)

In this case, the elasticity of substitution defined in 1.24 gives $\hat{Z_T} = \hat{V} = \hat{T_Z}$ since $t_{\hat{Z}T} = 0$. However, the resultant effect on labor supply depends on whether real net wage rises and outweighs the impact of the subsidies. The necessary change in the labor tax for the government to balance its budget when it changes s_{XA} and s_A is modified from 1.26 to:

$$\begin{aligned} \hat{t_L} &= -\frac{t_L}{1-t_L}\hat{L} - \frac{t_{ZT}Z_T}{(1-t_L)L}\hat{Z_T} + \frac{s_A A}{(1-t_L)L}\hat{A} \\ &+ \frac{(1-s_A)A}{(1-t_L)L}\hat{s_A} + \frac{s_{XA}X_A}{(1-t_L)L}\hat{X_A} + \frac{(P_X^D - s_{XA})X_A}{(1-t_L)L}s_{\hat{X}A} \end{aligned} \tag{C.1}$$

From the definition of σ_T and using $\hat{T_Z} = \hat{Z_T}$, I get: $\hat{T_A} = \hat{Z_T} - \sigma_T P_{\hat{T}A}$. Substitute for $\hat{T_A}$ from A.8, and for $\hat{A}$ from 1.23 into this expression:

$$\hat{X_A} = \hat{Z_T} + [\sigma_T\gamma_{XA} + \sigma_{TA}(1-\gamma_{XA})]s_{\hat{X}A} + (1-\gamma_{XA})(\sigma_T - \sigma_{TA})\hat{s_A} \tag{C.2}$$

Substitute for $\hat{A}$ from 1.23 into A.8, substitute the resulting expression for $\hat{T_A}$ into A.10 and use $\hat{T_Z} = \hat{Z_T}$ to get:

$$\hat{T} = (1-\alpha_{TZ})\hat{X_A} - \sigma_{TA}(1-\gamma_{XA})(1-\alpha_{TZ})(s_{\hat{X}A} - \hat{s_A}) + \alpha_{TZ}\hat{Z_T} \tag{C.3}$$

I know that $\hat{C} = \hat{X_C} = \hat{Y_C}$. Substitute C.3, C.2 that into the definition for σ_J:

$$\hat{X_C} = \hat{Z_T} + (\sigma_T - \sigma_J)(1-\alpha_{TZ})[\gamma_{XA}s_{\hat{X}A} + (1-\gamma_{XA})\hat{s_A}) \tag{C.4}$$

Substitute for $\hat{A}$ from 1.23 into C.1, and use the resulting expression in $\hat{w} = -\hat{t_L} + \phi_{XA}\hat{s_{XA}} + \phi_A\hat{s_A}$:

$$\begin{aligned}\hat{w} &= \frac{t_L}{1-t_L}\hat{L} + \frac{t_{ZT}Z_T}{(1-t_L)L}\hat{Z_T} - \frac{s_{XA}X_A + s_A A}{(1-t_L)L}\hat{X_A} - \frac{(\phi_{XA} - \sigma_{TA}s_A(A/I))}{(1-t_L)L}\hat{s_{XA}} \\ &- \frac{(\sigma_{TA}s_A(A/I) + \phi_A)}{(1-t_L)L}\hat{s_A} \end{aligned} \tag{C.5}$$

Add A.12 to A.13, and substitute for $\hat{A}$ from 1.23, use $L\hat{L} = L_Y\hat{L_Y}$ to substitute for $\hat{L_Y}$, substitute for $\hat{Y_C}$ from $\hat{X_C} = \hat{Y_C}$, substitute for $\hat{V}$ from $\hat{Z_T} = \hat{V}$, substitute C.4,C.2 and labor expression into the resulting expression:

$$(P_X^D X_C + Y_C)\hat{X_C} = -(P_Z^D Z_T + V)\hat{Z_T} - (P_X^D X_A + A)\hat{X_A} + L\hat{L} + \sigma_{TA}A(\hat{s_{XA}} - \hat{s_A}) \tag{C.6}$$

Substitute C.2, C.4, and 1.43 into C.6 to get 1.44. Change in ethanol consumption is obtained by substituting 1.47 and 1.49 into C.2:

$$\hat{X_A} = B_6\hat{Z_T} \tag{C.7}$$

where $B_6 = 1 + (\sigma_T\gamma_{XA} + \sigma_{TA}(1-\gamma_{XA}))(\frac{B_1B_5+B_2B_4}{B_4B_5}) + (\sigma_T - \sigma_{TA})(1-\gamma_{XA})\frac{B_4}{B_5}$. Substituting 1.47 and 1.49 into C.6, I get the change in consumption goods:

$$\hat{X_C} = \hat{Y_C} = \hat{C} = B_7\hat{Z_T} \tag{C.8}$$

where $B_7 = 1 + (1-\alpha_{TZ})(\sigma_T - \sigma_J)(\gamma_{XA}(\frac{B_1B_5+B_2B_4}{B_4B_5}) + (1-\gamma_{XA})\frac{B_4}{B_5})$. The change in ethanol consumption is obtained by substituting C.7,1.47 and 1.49 into 1.23:

$$\hat{A} = B_8\hat{Z_T} \tag{C.9}$$

where $B_8 = B_6 - \sigma_{TA}(\frac{B_1 B_5 + B_2 B_4}{B_4 B_5} - \frac{B_4}{B_5})$. The change in price per ethanol mile is obtained by substituting 1.47 and 1.49 into the definition for $\hat{P_{TA}}$ given in Section 2 to get:

$$\hat{P_{TA}} = B_9 \hat{Z_T} \tag{C.10}$$

where $B_9 = \gamma_{XA}(\frac{B_1 B_5 + B_2 B_4}{B_4 B_5}) + (1 - \gamma_{XA})\frac{B_4}{B_5}$. The change in ethanol miles is obtained by substituting C.10 into the definition of σ_T.

$$\hat{T_A} = B_{10} \hat{Z_T} \tag{C.11}$$

where $B_{10} = 1 - \sigma_T B_9$. The change in total miles driven is obtained by substituting C.11 and $\hat{T_Z} = \hat{Z_T}$ into A.10.

$$\hat{T} = B_{11} \hat{Z_T} \tag{C.12}$$

where $B_{11} = (1 - \alpha_{TZ}) B_{10} + \alpha_{TZ}$. The change in the overall price index is obtained by substituting 1.47 and 1.49 into the definition for change in P_J given in Section 2.2.

$$\hat{P_J} = B_{12} \hat{Z_T} \tag{C.13}$$

where $B_{12} = -[\phi_{XA}(\frac{B_1 B_5 + B_2 B_4}{B_4 B_5}) + \phi_A \frac{B_4}{B_5}$. The change in the price index of transportation is obtained by substituting 1.47 and 1.49 into the definition for change in P_T given in Section 2.2.

$$\hat{P_T} = B_{13} \hat{Z_T} \tag{C.14}$$

where $B_{13} = (1 - \alpha_{TZ}) B_9$. Substituting for C.7,1.47 and 1.49 into 1.43 I get change in labor supply as a function of $\hat{Z_T}$. Substituting resulting expression for $\hat{L}$, C.7,1.47 and 1.49 into 1.41 I get the change in labor tax as a function of $\hat{Z_T}$. Finally, substituting C.7,1.47 and 1.49 and the final reduced form expression for $\hat{L}$ into 1.42, I get the reduced form expression for the change in real net wage as a function of $\hat{Z_T}$.

Appendix D

θ is increasing in car quality

Proof: First note that $P_l^o < P_h^o$. If this was not true, then nobody would purchase low quality used cars. Now I need to show that types who buy w_h do not buy w_l, and vice versa. For this not to happen, the following incentive compatibility constraints must be satisfied:

$$\theta(w_h)w_h - P_h^o \geq \theta(w_h)w_l - P_l^o \Leftrightarrow \theta(w_h)[w_h - w_l] \geq P_h^o - P_l^o \tag{D.1}$$

$$\theta(w_l)w_h - P_h^o \leq \theta(w_l)w_l - P_l^o \Leftrightarrow \theta(w_l)[w_h - w_l] \leq P_h^o - P_l^o \tag{D.2}$$

Combining the two conditions, I get: $\theta(w_l)[w_h - w_l] \leq P_h^o - P_l^o \leq \theta(w_h)[w_h - w_l]$. If $w_l < w_h$, then the above condition implies that $\theta(w_h) > \theta(w_l)$ since $P_l^o < P_h^o$. Thus, there exists $\theta_h^o : \theta_l^o < \theta < \theta_h^o$ buy used cars of quality w_l, and $\theta_h^o < \theta < \theta_n^o$ buy good quality used cars. Similarly the types who purchase new cars have valuations for cars that are higher than those who purchase used cars of high quality. In other words, there exists $\theta_n^o : \theta_n^o < \theta < \overline{\theta}$ purchase new cars.

Appendix E

Optimal Subsidy when car quality is observable

Solving for each of the above endogenous variables in terms of the subsidy rate, S and P_n, I get:

$$\theta_h = \frac{(1+p)P_n - (1+p)\delta S - p(1-w_h)}{1 - w_h + (w_h - w_l)(1+\delta p)(1+p)} \tag{E.1}$$

$$\theta_n = \frac{\theta_h + p}{1+p} = \frac{(1+p)P_n - (1+p)\delta S - p(1-w_h)}{[1 - w_h + (w_h - w_l)(1+\delta p)(1+p)](1+p)} + \frac{p}{1+p} \tag{E.2}$$

$$P_h = \theta_h(w_h - w_l) + S = \frac{(1+p)P_n - (1+p)\delta S - p(1-w_h)}{1 - w_h + (w_h - w_l)(1+\delta p)(1+p)}(w_h - w_l) + S$$

$$\theta_{ls} = \frac{2}{1+p}\theta_h - \frac{1-p}{1+p} = \frac{2}{1+p}\frac{(1+p)P_n - (1+p)\delta S - p(1-w_h)}{1 - w_h + (w_h - w_l)(1+\delta p)(1+p)} - \frac{1-p}{1+p}$$

$$\theta_{lk} = \frac{S}{w_l} \tag{E.3}$$

$$P_l = S \tag{E.4}$$

Differentiation above set of solutions with respect to S:

$$\theta_h^1 = \frac{\partial \theta_h}{\partial S} = \frac{-(1+p)\delta}{1-w_h+(w_h-w_l)(1+\delta p)(1+p)} \tag{E.5}$$

$$\theta_n^1 = \frac{\partial \theta_n}{\partial S} = \frac{1}{1+p}\theta_h^1 \tag{E.6}$$

$$\theta_{lk}^1 = \frac{\partial \theta_{lk}}{\partial S} = \frac{1}{w_l} \tag{E.7}$$

$$\theta_{ls}^1 = \frac{\partial \theta_{ls}}{\partial S} = \frac{2}{1+p}\theta_h^1 \tag{E.8}$$

$$P_l^1 = \frac{\partial P_l}{\partial S} = 1 \tag{E.9}$$

$$P_h^1 = (w_h-w_l)\theta_h^1 + 1 \tag{E.10}$$

Social Welfare Function to be used to choose optimal subsidy rate:

$$\begin{aligned} W(S) &= \int_{\theta_n(S)}^{1} V_n(\theta,S)d\theta + \int_{\theta_h(S)}^{\theta_n(S)} V_h(\theta,S)d\theta + \int_{\theta_{lk}(S)}^{\theta_h(S)} V_{lk}(\theta,S)d\theta \\ &+ \int_{\theta_{ls}(S)}^{\theta_{lk}(S)} V_{ls}(\theta,S)d\theta + \int_{0}^{\theta_{ls}(S)} V_0(\theta)d\theta - \int_{\theta_{ls}}^{\theta_{lk}} \frac{S}{1-\delta}d\theta \\ &- \frac{\mu Q_E(\theta_h(S)-\theta_{lk}(S))}{1-\delta} \\ &= \int_{\theta_n(S)}^{1} \frac{\theta - P_n + \delta(pP_h+(1-p)P_l)}{1-\delta}d\theta + \int_{\theta_h(S)}^{\theta_n(S)} \frac{\theta w_h - P_h}{1-\delta}d\theta \\ &+ \int_{\theta_{lk}(S)}^{\theta_h(S)} \frac{\theta w_l - P_l}{1-\delta}d\theta + \int_{\theta_{ls}(S)}^{\theta_{lk}(S)} \frac{S-P_l}{1-\delta}d\theta - \frac{\mu Q_E(\theta_h(S)-\theta_{lk}(S))}{1-\delta} \\ &- \int_{\theta_{ls}}^{\theta_{lk}} \frac{S}{1-\delta}d\theta \end{aligned} \tag{E.11}$$

Differentiating the welfare equation with respect to S and set equal to zero:

$$
\begin{aligned}
(1-\delta)W'(S) &= -2(1-w_h)\theta_n\theta_n^1 + \delta p P_h^1 + \delta(1-p)P_l^1 - P_h\theta_n^1 - \theta_n P_h^1 \\
&- \delta(pP_h + (1-p)P_l)\theta_n^1 - \theta_n\delta(pP_h^1 + (1-p)P_l^1) + P_n\theta_n^1 \\
&- 2\theta_h(w_h - w_l)\theta_h^1 + (P_h - P_l) + \theta_h(P_h^1 - P_l^1) - 2w_l\theta_{lk}\theta_{lk}^1 \\
&+ \theta_{ls}P_l^1 + P_l\theta_{ls}^1 - \mu\partial Q_E(\theta_h^1 - \theta_{lk}^1) = 0 \qquad \text{(E.12)}
\end{aligned}
$$

Appendix F

Optimal Subsidy rate when quality is not observable

I substitute the reduced form solutions of each of the endogenous variables in terms of S, differentiate the welfare function and set it equal to zero to solve for S^*. The solution for w_u is as follows:

$$(A + BS)w_u + (D + ES) = 0 \tag{F.1}$$

where:

$$\begin{aligned}
A &= p(1+\delta p)(1+\delta)(w_h - w_l) \\
B &= p(1+\delta p)(w_h - w_l)P_n - 2pw_h(1+\delta)(1+\delta p)(w_h - w_l) \\
&+ w_h(1-w_h)(2-p)(1+\delta) \\
&- 2(1+\delta p)(w_h - w_l)(1-w_h) + p^2 w_h((1+\delta p)(1+\delta)(w_h - w_l)
\end{aligned}$$

Substituting the solution into each of the marginal conditions gives us solutions for the endogenous variables in terms of S. I then substitute each of these functions into the differentiated welfare function to get the optimal subsidy rate.

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